Hydrologic Impacts of Tile-Drained Landscape and Isotope Tracer Analysis

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Lu Zhang

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Joe Manger, Jeff Strock

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Preface

The impact of drain tiles was not very well documented. The purpose of tile installation was to reduce soil moisture and increase ventilation in the vadose zone to promote crop growth. Since the extensive tile installations in the 1900s, Minnesota has lost large amount of wetland as surface water storage. Reduction of the surface storage reduces water holding time and release water downstream at a higher rate. Drain tiles also altered subsurface hydrology. Prior to tile installation, subsurface water seeps into the streambank by capillary flow and preferential flow. Both are a lot slower than pipe flow. Once water enters the drain tile, it will move through and end up in the stream quicker than usual. Drain tiles are known for their potential to cause stream peak flow increases.

However, drain tiles don't allow control over soil moisture during drier season. Lack of soil moisture also negatively affect the yield. One of the agricultural best management practices, controlled drainage, let water to be held in the field by controlling the outlet of the tile. This practice also affects local hydrology by increasing residence time of water in the soil profile. Water quality is closely tied to hydrology as residence time is one of the controlling factors of biogeochemical processes in the soil.

This study investigated the hydrological impact of agricultural drain tiles and controlled drainage by:

- Estimating field water budget with field measured data including soil moisture and tile flow;

- Investigating tile drained landscape water characteristics by using stable water isotopes to perform hydrograph separation and estimate water mean transit time through different depths in the field.

Three tile drained fields were analyzed in this study: Beresford, SD, Tracy, MN, and Waseca, MN. All three sites had plots of the field functioning as controlled drainage and tile drainage for comparison purposes. Waseca site also had part of the field as perennial vegetation. This study found that although under a controlled drainage condition, water was kept in the field rather than let out through the tile, measured soil moisture content was lower than that of the drained condition, causing a decrease in the evapotranspiration. Controlled drainage could behave differently under various field conditions. Therefore, timing of release is critical to controlled drainage system and field monitoring data should be used to support decision making.

Stable isotopes of oxygen (oxygen-18) and hydrogen (deuterium) were used to investigate hydrologic characteristics for the three sites. Monthly hydrogen and oxygen stable isotope samples were collected for tile flow, well water, stream flow, precipitation, and soil water. Local meteoric water lines were established for the comparison of magnitude of evaporation from different sources at each location. Two end-member hydrograph separation was performed at each site on selected dates to partition tile drainage contribution to streamflow. The separation results showed significant contribution of tile flow to the streamflow.

Same isotopes were used to estimate the mean transit time of water through different depths in the fields. Lumped parameter modeling approach was applied to each data set to investigate the mean transit time of water through different depths of the field, such as groundwater and tile. This study found that precipitation water took an average of 9 months to move through different pathways and gain groundwater isotopic signature and an average of 4 months to gain tile water signature.

In summary, vadose zone is a complicated system. The information provided by the study helps gain understanding of average holding time of water in the soil profile before discharging out via tiles, the magnitude of tile water contribution to stream flow, and impact of controlled drainage on evapotranspiration. However, due to the limitation of sampling and monitoring, questions remain that how surface water and vadose zone water affects water budget. Also, the variation in the soil vertical structure can add difficulty to understanding the behavior of the system.

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1. Water Budget in Tile Drained Agricultural Landscape

1.1. Preface

Field water budget was not very well documented for tile drained systems. Drain tiles alter field hydrology by providing fast flow path to subsurface drainage. This greatly affects water availability in the soil, thus affecting evapotranspiration and percolation. Three tile drained fields were analyzed in this study: Beresford, SD, Tracy, MN, and Waseca, MN. All three sites had plots of the field functioning as controlled drainage and tile drainage for comparison purposes. Waseca site also had part of the field as perennial vegetation. Evapotranspiration was calculated for all three sites and different conditions using Penmen-Monteith method. Although under a controlled drainage condition, water was kept in the field rather than let out through the tile, measured soil moisture content was lower than that of the drained condition, causing a decrease in the evapotranspiration. This indicated that controlled drainage could behave differently under various field conditions. Therefore, timing of release is critical to controlled drainage system and field monitoring data should be used to support decision making.

1.2. Introduction

In the Midwestern corn-belt region, the extensive tile drain system provides a fast pathway for water to leave the field (Dinnes et al., 2002), greatly changing the local hydrology and drainage pattern. Compared to natural drainage, tiles remove water from surface and root zone, letting water out from a single pour point. The downstream hydrograph will have much higher peak flow with a shorter duration, causing a flasher stream. Crop yield highly depends on water availability in the root zone. Crop water use efficiency is a critical parameter to evaluate farm management and practice, and it is defined as a ratio of biomass accumulation to water consumption (Sinclair et al., 1984). Biomass accumulation can be expressed as carbon dioxide assimilation, total crop biomass, or crop grain yield. Water consumption can be expressed as transpiration, evapotranspiration, or total water input to the system. All these terms can be estimate through analysis of water balance. Being able to estimate how much water is available to the plant can help producers efficiently control field water content for highest yield with the help of controlled drainage.

Quantifying water budget/water balance is an important component of watershed hydrologic assessment not only because flooding is a safety and health concern to ecosystem and resident population, water quality is also highly depended on local hydrology. Hydrology affects water quality in two major ways: change in loading and change of residence time. Pollutant loading is calculated by multiplying pollutant concentration with runoff volume. Runoff volume is the outflow part of the water budget. Change of residence time happens mostly within the soil profile. Hydraulic residence time within the soil profile is determined by hydraulic conductivity in soil horizons. Change in the soil moisture content will change how fast water can move through root zone. The longer the water stays in the soil profile, the more time is available for biogeochemical processes to reduce the nitrogen load being leached into groundwater.

A water budget provides information on where water is stored and where water is going in a defined system. With changes in the climate pattern and precipitation, quantifying water budget will help better understand water availability for crops and help decision makers to adjust water management practices in the field based on crop needs. Quantifying water budget can be done to watershed of any size, closed system or open.

Controlled drainage is an agricultural best management practice (BMP) designed to manipulate water availability in the vadose zone. Controlled drainage alters the local hydrology by changing the soil moisture and water residence time in the root zone. From a water balance standpoint, increased soil water storage promotes both evaporation and deep percolation. When the soil is saturated, water availability no longer becomes a limiting factor for potential evapotranspiration and head pressure is increased to promote percolation.

Researchers have investigated certain component changes with the implementation of controlled drainage. The reduction in subsurface drainage was reported to be in the range of 10% to 40% (Riley et al., 2009; Gilliam and Skaggs, 1986; Fouss et al., 1987; Evans et al., 1995; Skaggs et al., 1995a, 1995b; Drury et al., 1997; Amatya et al., 1998; Tan et al., 1998). Surface runoff had an increase of 68% according to Skaggs et al. (1995b) and 54% by Riley et al. (2009).

This study will quantify field water budget of three tile-drained fields located in Waseca and Tracy, MN, and Beresford, SD, and assess the impact of altering drainage in these fields.

1.3. Method

1.3.1. Site Description

The three sites from east to west are Waseca, Tracy, and Beresford (Figure 1-1). Waseca site’s major soil type is slowly drained Webster clay loam. There are three plots at Waseca site: drained cropland, undrained natural vegetation, and undrained cropland.

Drained cropland is drained by a 4" tile and the natural perennial vegetation and undrained cropland are both natural drainage within tile installed. Tracy site's major soil type is moderately-drained Havelock clay loam. There are two types of plots at Tracy: two drained cropland and one undrained cropland. The drained plots are drained by 4" tile. Beresford site's major soil type is slowly drained Egan-Trent silty clay loam. Similar as Tracy, there are only two types of plots: drained and undrained. To represent undrained condition, the tiles in these plots (1, 4, 5 in Figure 1-2) were plugged to allow no tile flow through. Drain tiles are installed at a depth of 1.2 meters at all three sites. This water balance analysis was performed between soil surface (0 mm) and tile depth (1200 mm).

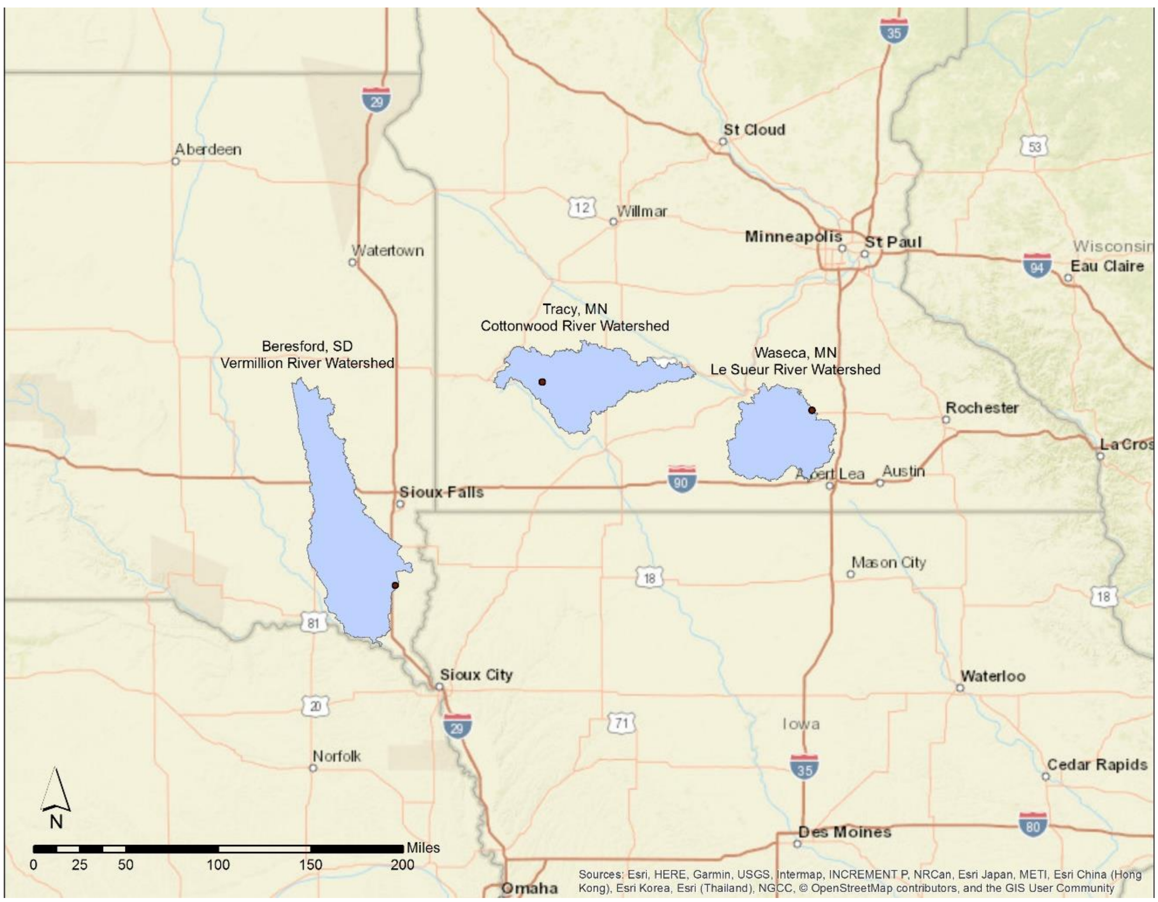


Figure 1- 1. Site map of fields analyzed and their location in the local watershed

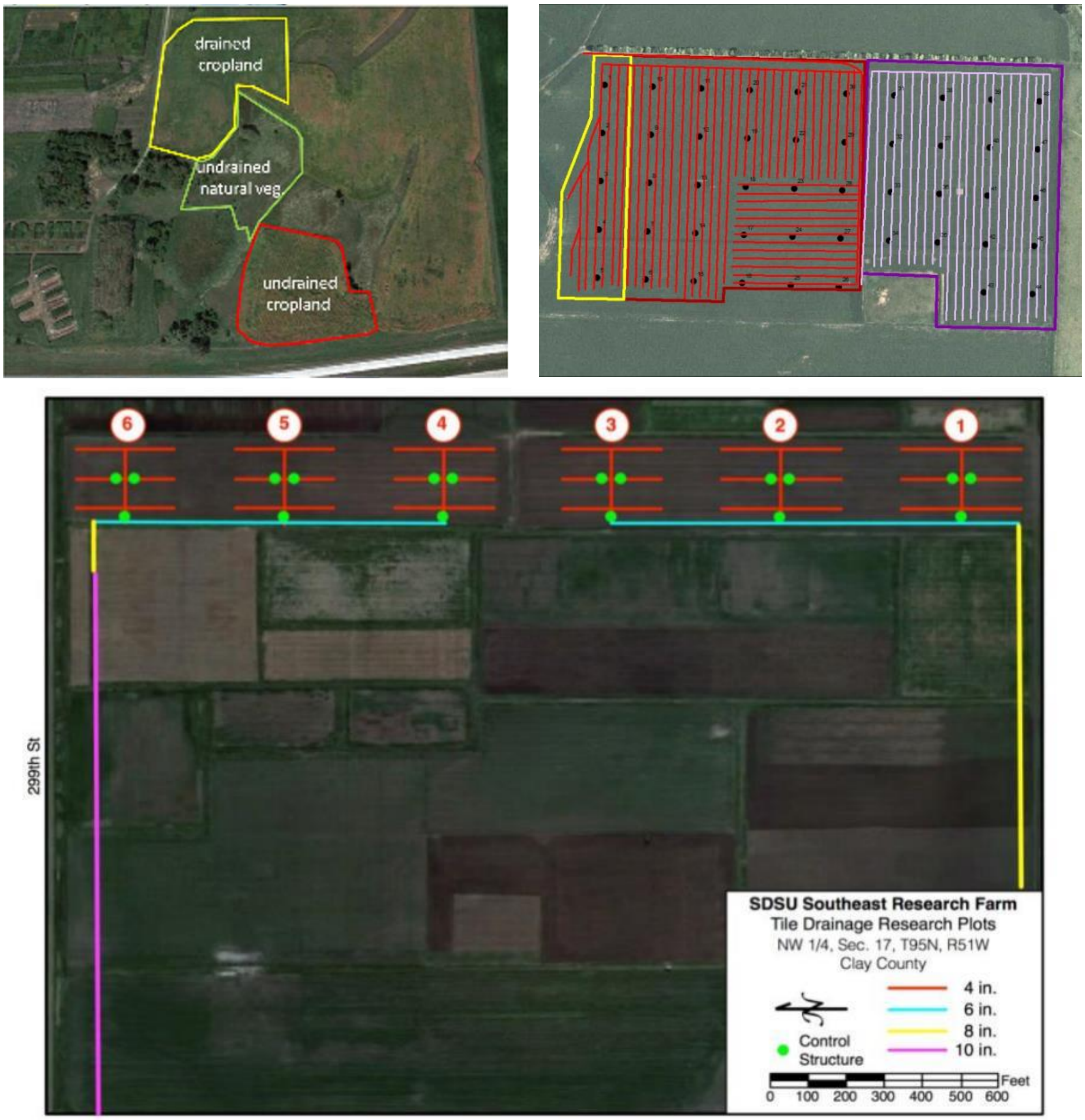


Figure 1- 2. Drainage plots at Waseca, Tracy, and Beresford sites. Top left is Waseca site: from top to bottom are drained cropland, undrained natural vegetation, and undrained cropland; top right is Tracy site: from left to right are undrained cropland, west drained cropland, east drained cropland; bottom is Beresford site: plot 2, 3, 6 are drained croplands and plot 1, 4, 5 are undrained croplands

1.3. 2. Weather Condition

Water budget is highly impacted by precipitation as it's a major source of the water input. The average annual precipitation depths of the three sites are very different. Precipitation has an increasing pattern from west to east. During the years of analysis (2016 and 2017), Beresford received an average annual rainfall of 79 cm, Tracy 87 cm, and Waseca 115 cm.

1.3.3. Water Budget Estimation

A general form of water balance was used to investigate the field water balance (Equation 1). The change in water storage ($\frac{dS}{dt}$) within the watershed equals the difference between input and outflow.

$$\frac{dS}{dt} = P - Q - ET \quad (1)$$

Where:

P is precipitation;

Q is outflow;

ET is evapotranspiration.

For a corn field, inflow water is precipitation, and water storage is reflected by soil moisture level. Outflow includes components of percolation, lateral flow, overland runoff, and tile drainage.

Precipitation data was obtained from local weather stations. Snowfall was converted to equivalent rainfall depth in the precipitation records. Figure 1-3 shows the snow water equivalent of Minnesota in March. Daily tile flow data was recorded from all tile outlets at the field.

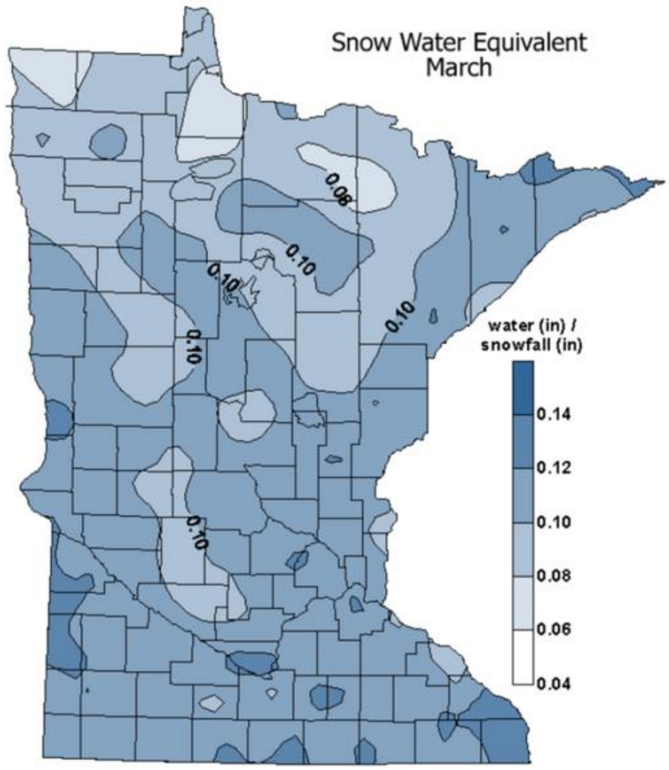


Figure 1- 3. Minnesota Snow Water Equivalent (Stormwater Manual, MPCA)

Daily evapotranspiration (ET) rate was calculated using the Penman-Monteith equation method. Alfalfa was used as the reference crop. Reference ET (RET) was calculated using Equation 2 and actual ET (AET) was calculated using Equation 3.

$$RET = \left(\frac{\Delta}{\Delta+\gamma_c^*} * R_n + \frac{\rho C_p}{\Delta+\gamma_c^*} * \frac{e_a^s - e_a}{\Re_{ah}}\right)/L \tag{2}$$

$$AET = RET * k_c * k_w \tag{3}$$

Where:

Δ is slope of psychrometric saturation line (mbars/C), $\Delta = \frac{5336}{T^2} * \exp\left(19.05 - \frac{5336}{T}\right)$, T is mean air temperature in degrees K;

γ_c^* is the calculated as $\gamma_c^* = \gamma_c(1 + \frac{R_{lv}}{R_{ah}})$, γ_c is the psychrometric constant being 0.066 KPa/K; R_{lv} is stomatal resistance calculated using leaf area index (LAI); R_{ah} is the atmospheric resistance calculated as $R_{ah} = \frac{(\ln\left(\frac{z-d}{Z_h}\right)-\psi_h)(\ln\left(\frac{z-d}{Z_m}\right)-\psi_m)}{\kappa^2 U(z)}$; $\psi_h = \psi_m = 0$ for neutral conditions and $\kappa = 0.41$; $Z_m = 0.123\bar{h}$ and $d = 0.67\bar{h}$, $Z_h = 0.1Z_m$; $\bar{h}$ is the average height of the crop canopy;

R_n is the net radiation (W m^{-2});

ρ is the dry air density (kg m^{-3}), C_p is the specific heat capacity of air (kJ kg^{-1} K^{-1}), $\rho C_p = 1.006$;

e_a^s is the saturated vapor pressure, $e_a^s = \exp\,(19.05 - \frac{5336}{T_{in\ kelvin}})$;

e_a is the air vapor pressure, $e_a^s - e_a = e_a^s * T - e_a^s(\frac{T_{min}rh_{max}+T_{max}rh_{min}}{2})$

L is the latent heat of vaporization (MJ m^{-3}), calculated as $L = 2495 - 2.1777 * T$;

k_c is crop coefficient;

k_w is water stress factor, calculated based on evaporative demand, Larson (1985) suggested the following relationships, where demand K_w is determined by pan evaporation.

High demand: $K_w = -0.15 + 1.53\frac{A_w}{100}\ for\ 9.8\% < A_w < 75\%$

Moderate demand: $K_w = 0.16 + 1.68\frac{A_w}{100}\ for - 9.5\% < A_w < 50\%$

Low demand: $K_w = 0.57 + 1.72\frac{A_w}{100}\ for - 33\% < A_w < 25\%$.

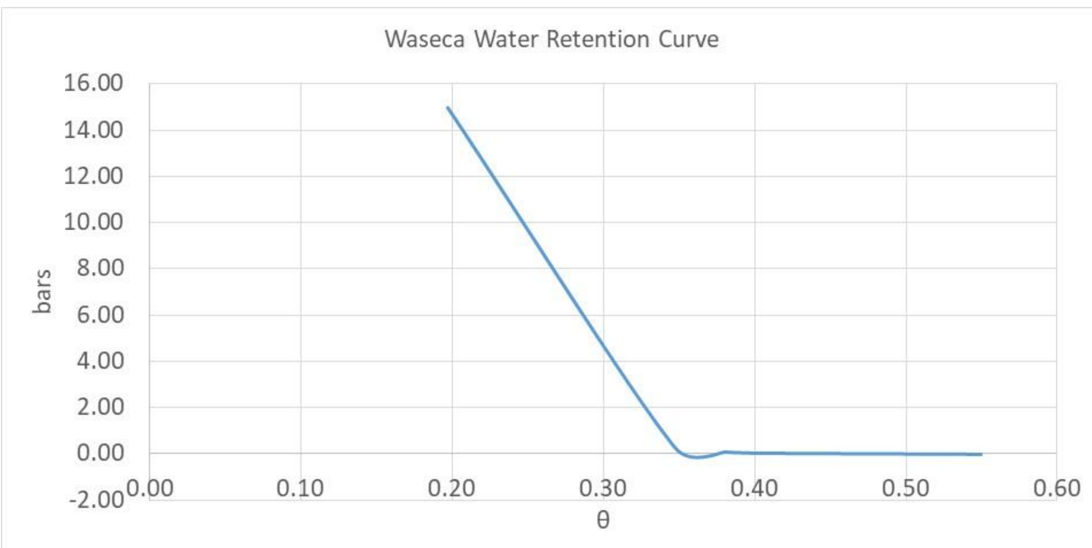
The following table (Table 1-1) summarized crop coefficient for corn and assumed growing stages based on Ji et al. (2017) and Burman et al. (1983).

Table 1- 1. Crop coefficients

Stage	Julian Days	Kc (corn)	Kc (perennial)
Initial	111	0.18	0.9

Maximum	153	0.95	0.95
	259	0.95	0.95
Late-season	306	0.18	0.9

Measured moisture data was used for the water availability factor calculation. Due to the difference in soil types, wilting point and field capacity soil water content can be quite different among the sites. These parameters were determined based on previous measurements. Water retention curves for Waseca and Beresford site were available (Figure 1-4 and Table 1-2). Average soil moisture was used for each field. On days with no measurement, soil moisture was estimated based on the water retention curve and previous day soil moisture. Water retention curve at Tracy site was not available. Since Tracy and Waseca both had clay loam soil, assumption was made that they share the same soil water retention characteristics.



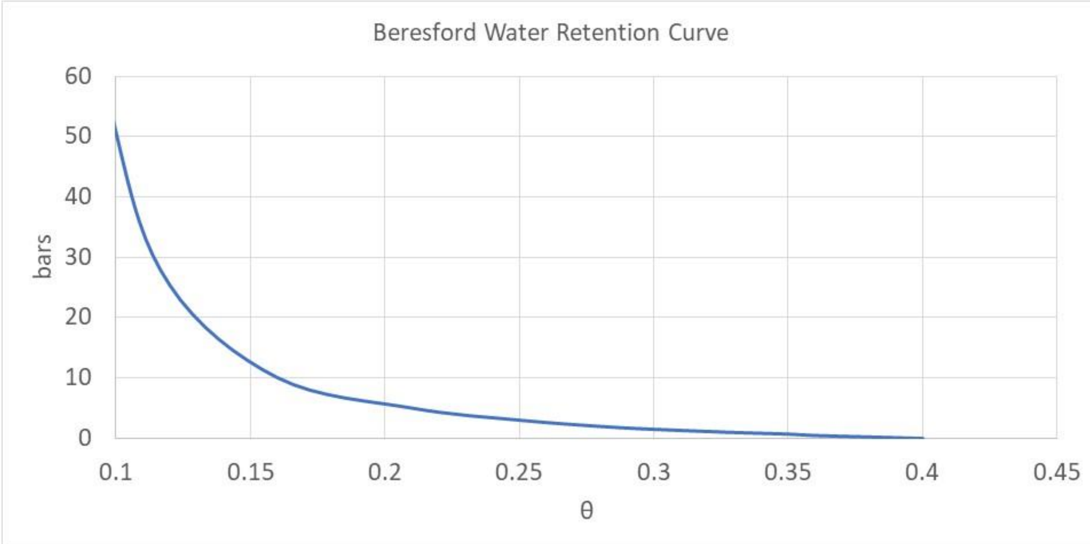


Figure 1- 4. Soil water retention curves for Waseca and Beresford sites

Table 1- 2. Soil water content for wilting point and field capacity

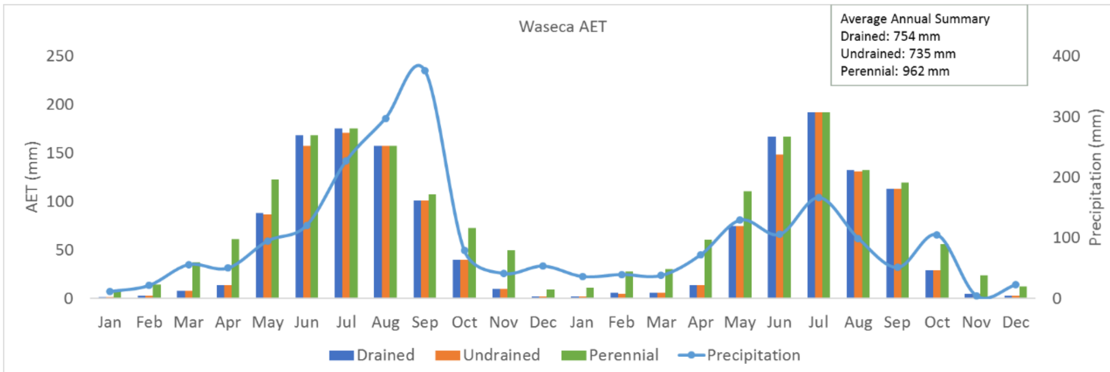
Stage	Wilting Point	Field Capacity
Waseca	0.2	0.35
Tracy	0.2	0.35
Beresford	0.15	0.38

Overland runoff is an important component of the outflow that was not included in the water budget analysis in this study. Implementation of tile drains allows water to pass through vadose zone quickly and redirects a portion of the surface flow to subsurface tiles, reducing the amount of surface runoff. However, the effect of surface runoff could be reflected in the soil moisture changes. This was discussed in later sections.

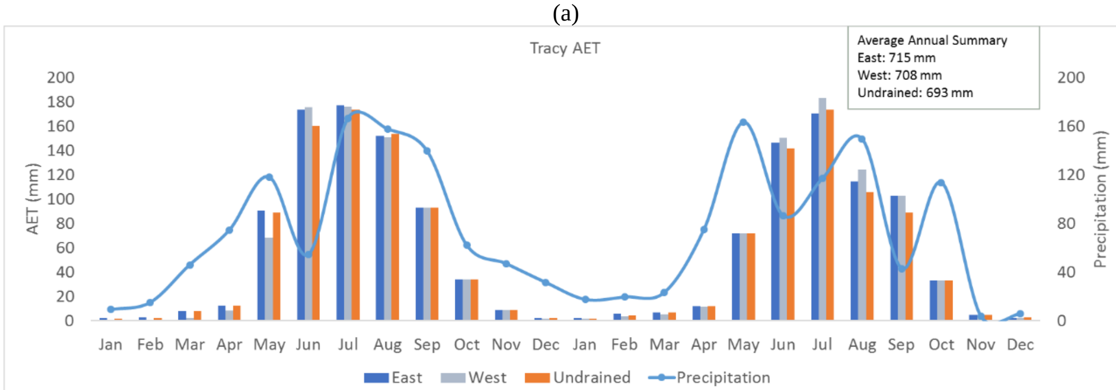
The water balance was performed on a depth unit. Both precipitation and evapotranspiration were available as depth. Tile flow depth, however, was measured in the pipe and was different from average depth across the field. Therefore, a total daily tile flow volume was calculated and was divided by the field area.

1.4. Results

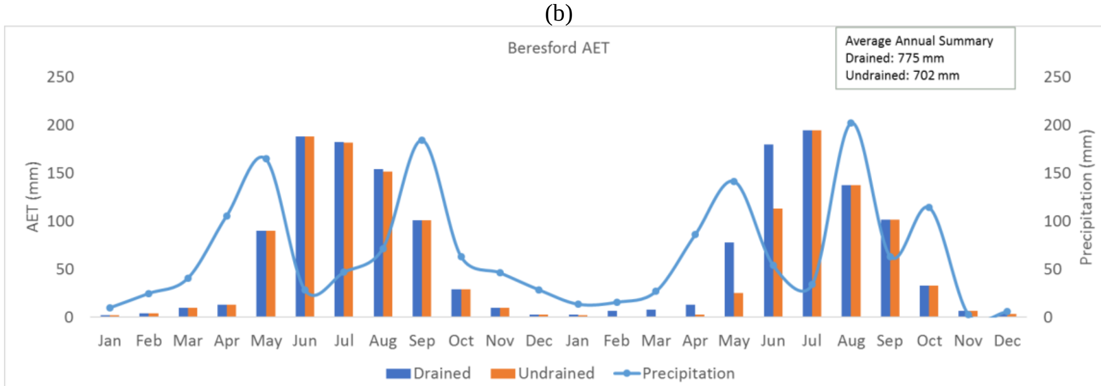
Results of the AET estimation of the three sites are presented below (Figure 1-5). Corresponding ET amount was summarized in numbers on each graph.



(a)



(b)



(c)

Figure 1- 5. Predicted actual ET by Penman-Monteith method using alfalfa as reference crop: (a) result from Waseca field; (b) result from Tracy field; (c) result from Beresford field

It was interesting to see that the undrained fields had less ET than drained fields at all three locations. This difference was particularly significant during the summer months.

A different study observed similar summer months conditions. Rijal et al. (2010) measured ET rates using eddy covariance system and observed 11.5% more ET in subsurface drainage field than undrained field.

Khand et al. (2017) estimated ET during growing season at two sites using Landsat imagery-based METRIC (Mapping Evapotranspiration at high Resolution with Internalized Calibration) model: Wahpeton, ND and Beresford, SD. Wahpeton had corn in 2009 and soybean in 2010; Beresford had corn in 2013. The results for Beresford site were shown in Figure 1-6 for comparison purposes. The following conclusions can be drawn from the comparison:

- From May through September, both studies predicted ET within the similar range of magnitude;
- Both studies predicted the greatest monthly ET occurred in July;
- Both studies had months where ET from drained field exceeding undrained field;
- Khand et al. (2017) concluded that daily ET from drained and undrained fields were not statistically significant ($p>0.05$); however, this dissertation study (Zhang, 2019) showed a p-value of 0.049, which is significant.

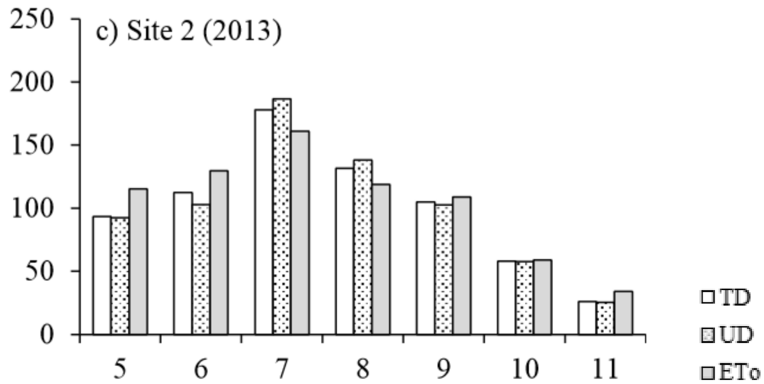
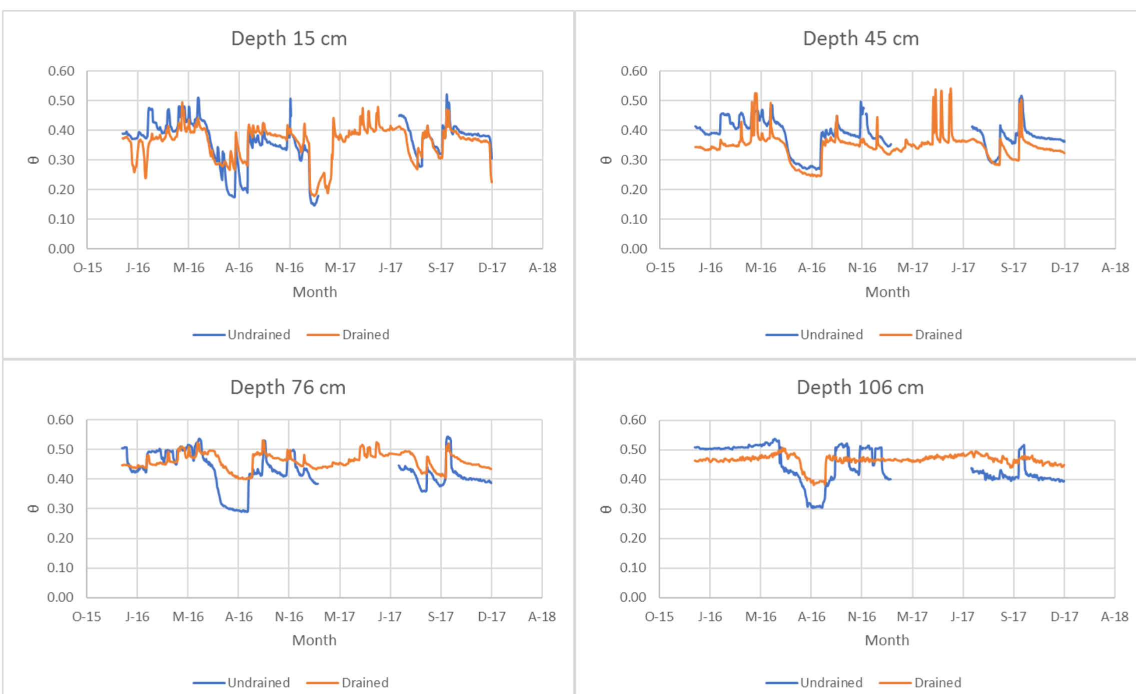


Figure 1- 6. Beresford monthly ET from subsurface drained (TD) and undrained (UD) fields using METRIC and monthly ETo estimated from weather data during the study years; x-axis is month and y-axis is monthly ET or ETo in mm (Khand et al., 2017)

To further examine the difference between the drained and undrained fields in Beresford, Figure 1-7 was created to compare the measured soil moisture content. The depth of the tiles at Beresford was 4 ft with 50 ft spacing, lower than the soil moisture sensors. The graphs show that undrained field had a relatively high soil moisture level till the growing season and dropped below drained field.



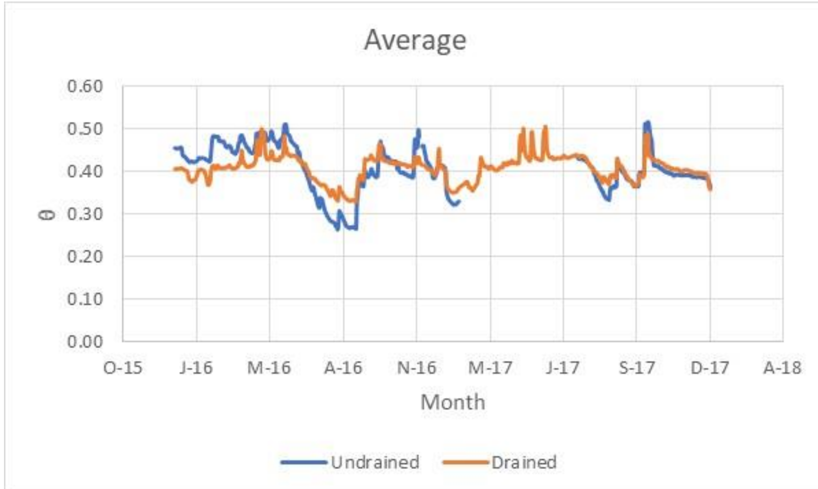
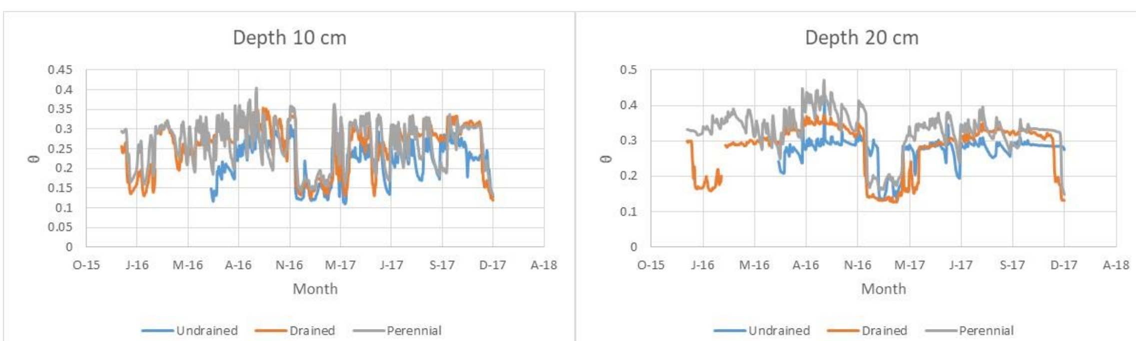


Figure 1- 7. Beresford daily soil moisture measurements at different soil depth

Since same result was seen at Waseca and Tracy as well, soil moisture data was examined for those two sites (Figure 1-8 and 1-9). In Waseca, the undrained plot soil moisture was almost constantly lower than drained field above tile drain depth. At Tracy, east and west field had the same cropping management. Therefore, the predicted ET amounts were quite similar. Undrained plot at Tracy site was slightly lower in average annual ET in the drained plots.



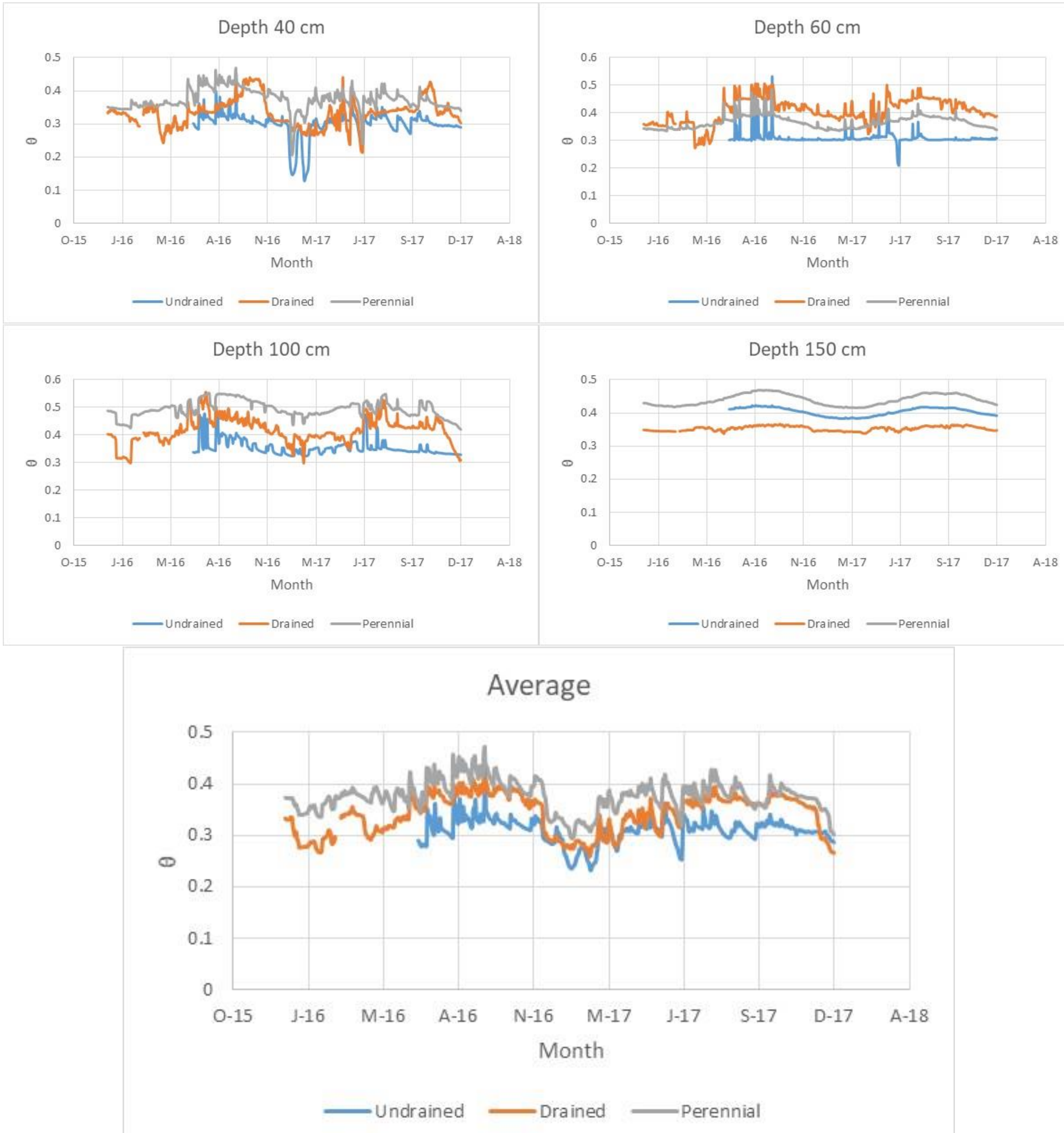
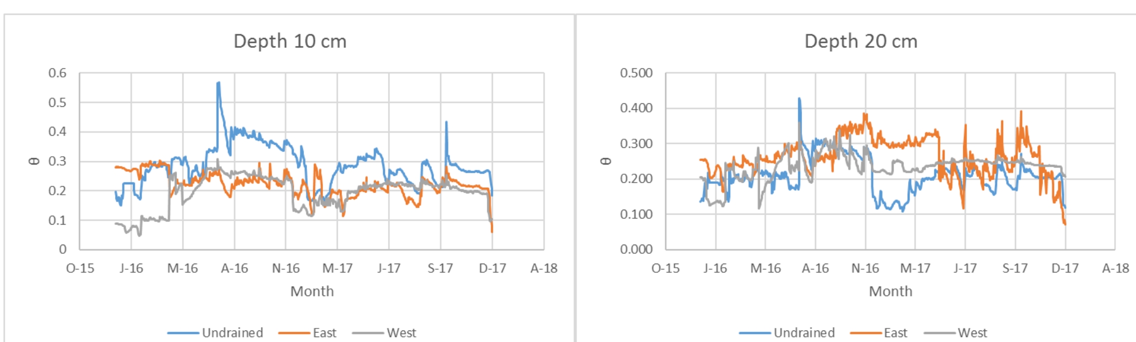


Figure 1- 8. Waseca daily soil moisture measurements at different soil depth



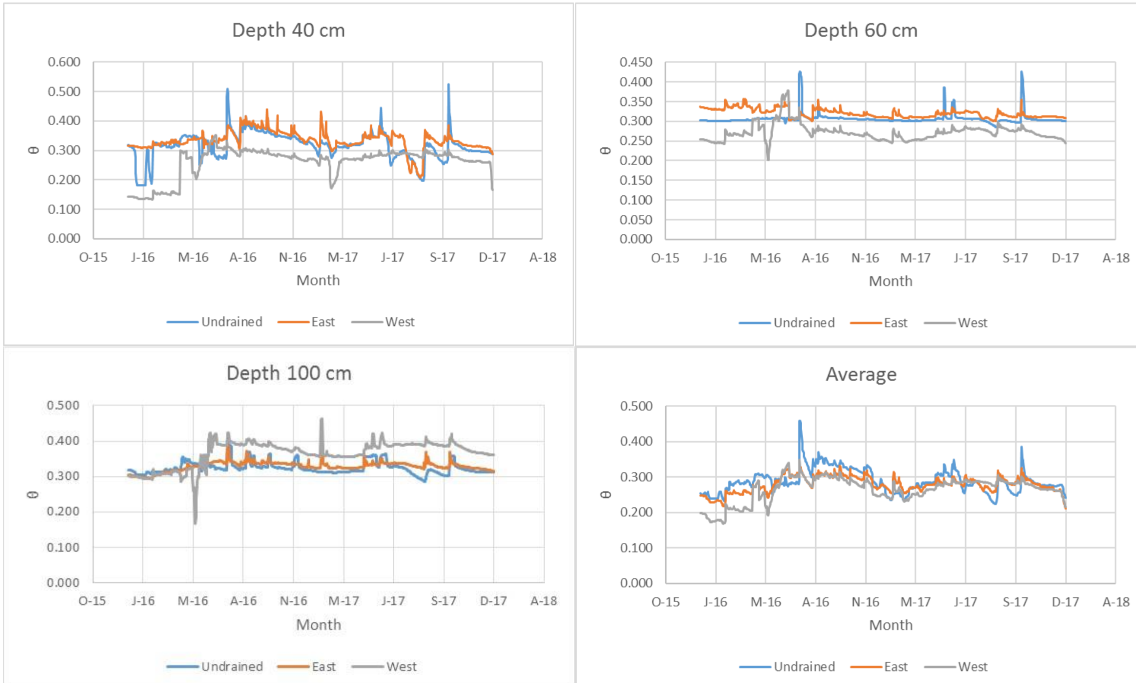


Figure 1- 9. Tracy daily soil moisture measurements at different soil depth

From the water balance equation (Equation 1), change of soil water storage is a result of input water minus outflow water. Change of soil water storage was calculated using the start and end of the monthly soil water content. When the equation was re-arranged, it became:

$$Q - Tile\ Outflow = P - ET - \frac{dS}{dt} - Tile\ Outflow \qquad (4)$$

This calculated difference represents the sum of all other outflows except for tile outflow, including percolation, lateral flow and overland runoff. The calculated difference is shown in the table below (Table 1-3).

Table 1- 3. Input and output water difference

Month	Waseca Drained	Waseca Undrained	Waseca Perennial	Tracy E Drained	Tracy W Drained	Tracy Undrained	Beresford Drained	Beresford Undrained
Jan-16	73.8	-98.6	38.0	22.9	35.2	24.7	26.2	43.0
Feb-16	-12.3	17.3	-19.1	-3.0	-27.8	-42.1	2.1	-44.7
Mar-16	-3.1	48.4	-7.5	18.4	32.4	32.0	-2.5	16.1
Apr-16	75.5	42.1	-14.9	69.0	-31.8	37.9	-83.5	85.7

May-16	-54.6	8.2	-21.8	22.4	11.2	43.6	-529.6	51.2
Jun-16	-97.5	46.2	-29.6	-105.4	-149.3	-97.0	-202.4	-18.4
Jul-16	39.4	26.4	39.9	-76.4	10.2	-71.9	-64.7	-19.0
Aug-16	119.4	109.7	99.2	-73.9	-41.1	-18.8	-58.7	-64.5
Sep-16	264.7	272.2	278.0	11.7	52.0	68.3	-31.7	-60.8
Oct-16	-0.4	39.5	2.1	1.0	17.6	35.0	-37.4	-4.2
Nov-16	60.0	30.3	-10.6	28.6	38.6	31.9	34.5	66.6
Dec-16	144.1	94.8	136.6	58.5	76.5	94.5	39.5	-15.4
Jan-17	37.1	56.5	34.6	-15.0	-9.3	38.1	49.1	391.7
Feb-17	19.0	-1.5	-27.4	42.3	34.6	0.8	-36.2	-31.0
Mar-17	-22.9	35.1	-5.0	-124.4	4.2	-1.2	9.2	4.8
Apr-17	47.3	52.6	-4.3	16.8	51.5	40.7	47.7	74.1
May-17	48.6	97.3	67.5	19.6	92.9	106.2	141.5	131.2
Jun-17	-132.3	-73.3	-86.9	-112.4	-68.3	-31.3	-66.6	-334.2
Jul-17	-72.1	-23.2	-40.0	-5.5	-62.6	-9.3	-102.6	-84.8
Aug-17	-51.2	-36.3	-26.1	-32.1	19.3	-10.5	35.8	24.4
Sep-17	-44.2	-64.2	-31.3	-79.8	-54.4	-12.1	-7.3	-26.9
Oct-17	55.2	79.3	6.8	81.4	49.0	50.9	-47.0	84.9
Nov-17	18.0	11.0	-0.7	14.8	4.7	3.5	4.6	6.5
Dec-17	121.2	43.5	92.3	83.6	62.2	46.6	37.5	36.8
Total	632.7	813.2	469.8	-136.6	147.6	360.3	-842.6	312.9

1.5. Discussion

It was interesting to see the tile-drained plots having more annual total ET than plots with no tiles. First, these plots weren't in a perfect controlled environment. The plots were not separated by vertical barrier, making lateral flow possible to occur. As shown in Table 1-3: positive numbers mean that to achieve the measured soil moisture change, this much water was discharge out of the plot through percolation, lateral flow, or overland runoff in the month; and negative numbers mean that in addition to precipitation input, the plot needed to receive this much water from groundwater upwelling, lateral flow, or overland runoff coming in to support the soil moisture change.

Properly designed and installed drain tiles can help produce healthier crops by reducing the amount of inundation in the root zone. A healthier crop is likely to have a higher transpiration rate. This could be a possible reason why drained plots AET exceeded the undrained plots during growing seasons (Figure 1-5 and Figure 1-6).

Since the predicted AET highly depends on the soil moisture measurements to estimate water stress factor, there could be errors due to the soil moisture sensor placement bias. Most of the sensors were placed near the edge of the field where lateral flow between the plots could be more significant than the center of the field. Also, in Tracy, the underlying soil isn't uniformly loam. There are pockets of sandier soil at unknown locations in the field. Although not observed from the soil borings, it could cause uneven distribution of water in the field, making sensor reading not representative.

1.6. Conclusion

For most of these fields, rainfall was not the only input in the water balance equation. Both soil moisture measurements and water balance calculations indicated the important roles groundwater level change, lateral subsurface flow and overland runoff played. The proximity of undrained/controlled drainage field to tile-drained field or perennial field can result in misleading soil moisture content readings. Future research should aim to quantify lateral flow magnitude and have better control for different drainage/planting condition to minimize interference. It is also important to closely monitor soil water content when implementing controlled drainage to avoid unexpected field moisture condition and minimize impact on crop growth.

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2. Sourcing and Pin-Pointing Streamflow in Tile-Drained Agricultural Landscape with Hydrograph Separation Using Stable Isotopes

2.1. Preface

Stable isotopes of oxygen (oxygen-18) and hydrogen (deuterium) were used to investigate hydrologic characteristics in a drained agricultural landscape. Evaporation and condensation cause water to fractionate, changing the percent composition of oxygen and hydrogen isotopes in the residual water. The differences in the input and output of water isotopic composition enables researchers to gain more information on various hydrologic characteristics including water mixing sources, transit time, evaporation magnitude, groundwater recharge rate, etc. Monthly hydrogen and oxygen stable isotope samples were collected at the following field research sites: Beresford, SD, Tracy, MN, and Waseca, MN. Local meteoric water lines were established for the comparison of magnitude of evaporation from different sources at each location. These included, but not limited to, soil water, shallow well, deep well, tile and river. Two end-member hydrograph separation was performed at each site on selected dates to partition tile drainage contribution to streamflow. The separation results showed that, from west to east, tile drain contributes about 49%, 64% and 50% of the streamflow.

2.2. Introduction

The implementation of tile drains altered the local hydrology by providing a “shortcut” for water to travel through the field. Therefore, water moves through the field faster and more ends up in the downstream receiving water in a shorter time. Schottler et al. (2013) examined 21 watersheds across the Minnesota and concluded that among which, watersheds with large land use changes experienced increase in season and annual water yields of greater than 50% since 1940. This increase is highly correlated with artificial drainage and loss of depressional areas.

The major negative impacts of tile drains on local hydrology are less residence time in soil water storage and flashier streams. Looking beyond the direct impacts, this could also discourage evapotranspiration (ET), induce erosion, and reduce water availability for plants, thus reducing production.

Controlled drainage is one of the agricultural best management practices (BMP) designed to manage root zone moisture condition. By installing a control structure at the outlet of the drain tile, landowners will be able to manually control the water level in the field to retain the most water without damaging the plant roots (Minnesota Department of Agriculture). Controlled drainage also provides nutrient removal benefit by increasing the residence time of water in the field. However, controlled drainage may have a similar impact as the conventional tile drains for releasing water downstream, except that controlled drainage is likely to release a larger amount in a limited time period.

Better understanding of the impact of tile drainage on local hydrology is important to agricultural management practices and programs. Hydrograph separation is one of the methods widely used to study the source of streamflow and the contribution from each source. Hydrograph separation helps quantify the percent contribution of each end member. Two-component hydrograph separation is most commonly seen. It means two water sources are accounted for. When more constituents are measured, more components/sources can be included to better describe watershed processes.

The common two end-members are event water and pre-event water (Klaus & McDonnell, 2013). Stream water is commonly composed of groundwater, rainfall, overland runoff, shallow groundwater seepage, and, specifically for tile drain system, tile drainage. All the above components can be considered as event water. Assumptions to neglect certain sources is necessary in calculations to reduce the complexity of the model. Major components such as groundwater and/or tile drainage are commonly used.

Hydrograph separation is commonly performed with environmental tracers, conservative tracers, semi-conservative and reactive tracers (Bertrand et al., 2014). Conservative tracers are tracers that don't get affected by biogeochemical processes during transport, such as chloride and oxygen stable isotope. Non-conservative tracers like nitrate changes concentration during the transport. Numerous studies have investigated watershed characteristics using tracers and hydrograph separation.

Tomer et al. (2010) used hydrograph separation method to separate tile outflow hydrographs into discharge from tile line and surface intake component for water quality purposes at Tipton Creek watershed, Iowa. He concluded that surface intakes were responsible for 13% of tile discharge and subsurface tiles dominate the nitrate delivery based on the nitrate concentration measurement at locations.

Contribution of tile drainage to stream varies based on location. Amado et al. (2017) found that tile drain contributes approximately 15% to 43% of total annual streamflow in Northeast Iowa using end-member analysis with nitrate concentrations. This value is dependent on precipitation. In a wet year, excessive precipitation allows more volume of water to infiltration, increasing discharge from tiles. This can cause a higher percent contribution of tile flow to streamflow.

Schilling and Helmers (2008) examined hydrographs of tile-drained watershed in the Walnut Creek watershed in Iowa using hydrologic models. They concluded that tile drainage primarily affects the baseflow portion of a hydrograph and tile drainage increased the groundwater contribution to surface water.

The question this study seeks to answer is how tile drain system affects local field level hydrology. To further explore the impacts, stable isotope tracers were used to perform event hydrograph separation at each site. Major end members were assumed to be tile drain, groundwater or soil water. A sensitivity analysis was completed for each site to test for the impact of each parameter.

2.3. Sampling and Method

Hydrogen and oxygen stable isotopes have been used in water science related research to help understand hydrologic pathway and mixing mechanisms. They have also been used to study lake evaporation, waterbody residence time, and extreme event impacts on local hydrology (Fritz and Fontes, 1980; Simpson and Herczeg, 1991; Payne and Yurtsever, 1974; Burns and McDonnell, 1998; Zhang and Magner, 2014).

Hydrogen and oxygen isotopes used in this study are deuterium (D) and oxygen-18 (^{18}O). Deuterium is one of the two stable isotopes of hydrogen. It is heavier than protium. Hydrogen also has a third isotope, tritium, which is the heaviest and radioactive. The half-life of tritium is 12.3 years. Protium comprises about 99.985% of the hydrogen atoms in the atmosphere, whereas D only accounts for 0.015% (Mook, 2001). Oxygen has three isotopes as well: ^{16}O (99.895%), ^{17}O (0.038%), and ^{18}O (0.2%). All three isotopes are stable.

Vienna Standard Mean Ocean Water (VSMOW) is a universal standard set by International Atomic Energy Agency (IAEA) for comparison of heavy isotopes as they are usually in trace amount. The following equations are used for calculating the relative abundance of D and ^{18}O:

$$\delta D\ (‰) = \left(\frac{R_{sample}}{R_{VSMOW}} - 1\right) * 1000 \tag{1}$$

$$\delta^{18}O\ (‰) = \left(\frac{R_{sample}}{R_{VSMOW}} - 1\right) * 1000 \tag{2}$$

Where:

R equals to ${}^{2}_{1}H/{}^{1}_{1}H$ and ${}^{18}_{8}O/{}^{16}_{8}O$, respectively;

and δ represents the ratio.

2.3.1. Sampling

Isotope samples were collected monthly from three locations: Beresford, SD in the Vermilion River Watershed, Tracy, MN in the Cottonwood River Watershed, and Waseca, MN in the Le Sueur River Watershed (Figure 2-1). The climate pattern from west to east, shows increased rainfall. The annual average for the past 10 years is 70.4 cm for Beresford, 71.1 cm for Tracy, and 94 cm for Waseca.

At each site, isotope samples were gathered from subsurface drain tile, groundwater well, and river each month during the flowing season. For the Tracy site, additional samples were collected from suction cup lysimeter, piezometer, and a surface wetland. Table 2-1 shows the depths of the subsurface sample locations. Precipitation samples were collected when available. Samples were stored in tightly capped bottles at room temperature prior to analysis to prevent evaporation and condensation induced fractionation.

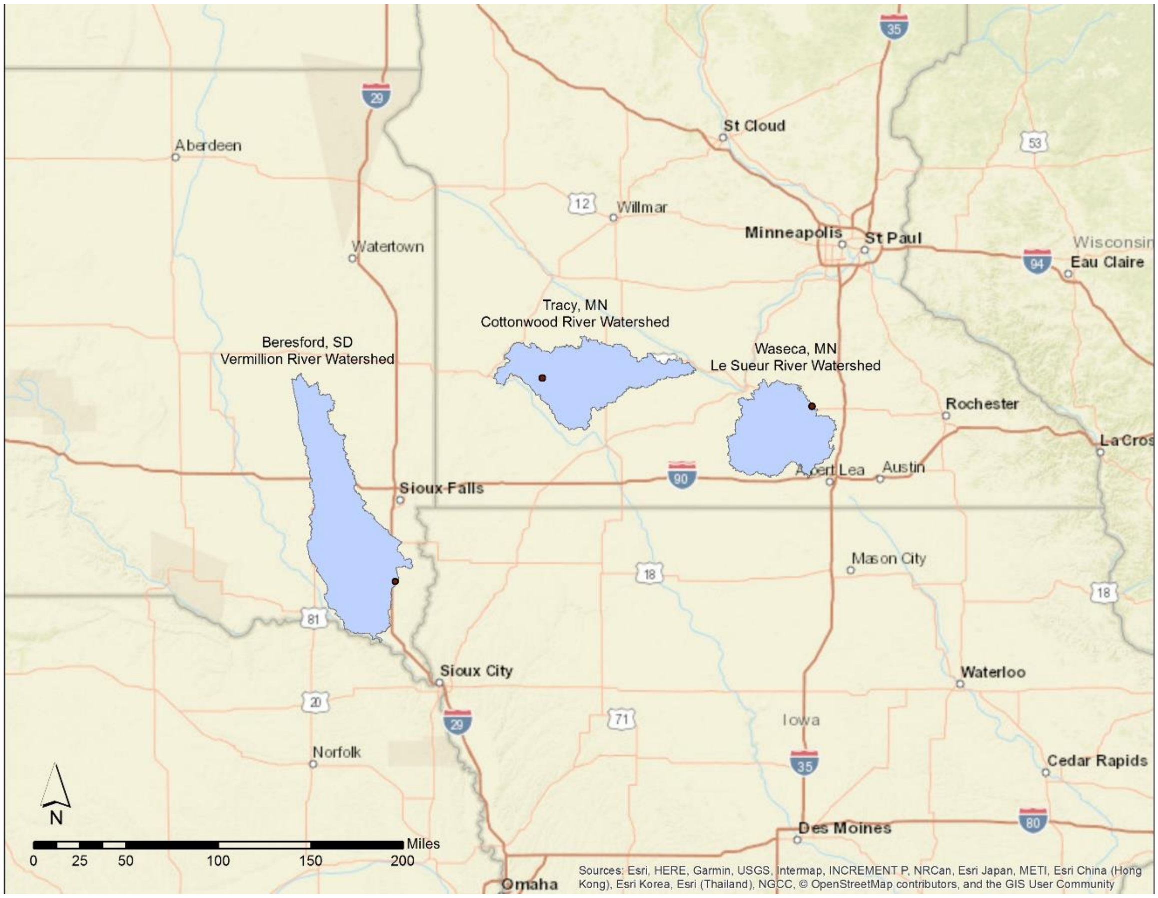


Figure 2- 1. Subsurface sampling depth at each site (from shallow to depth)

Table 2- 1. Subsurface sampling depth at each site (from shallow to depth)

Sampling Location	Waseca	Tracy	Beresford
Lysimeter	-	0.76 m	-
Drain tiles	1.2 m	1.2 m	1.2 m
Shallow well	-	-	1.5 m
Piezometer	-	2.4 m	-
Deep well	13.1 m	10.7 m	10.7 m

The university-level lab used laser spectroscopy system (Liquid Water Analyzer, DLT-100, Los Gatos Research, Inc) coupled to a PAL autosampler for simultaneous measurements of D/H and $^{18}O/^{16}O$. The precision of δD is ±1.0‰ and that of $\delta^{18}O$ is

±0.25‰. A standard was run after every two unknown samples to correct for any instrumental drift and errors (Xiao, 2015).

2.3.2. Meteoric Water Line

Meteoric water line (MWL) is established by plotting δD against $\delta^{18}O$ from meteoric water, aka precipitation. The global MWL plots samples from across the globe to establish an average slope of 8 (Mook, 2001). When plotting samples from one region, the local MWL tends to deviate from the global average due to the source of the water vapor. The ocean is rich in ^{18}O as ^{16}O evaporates first. When tropical cloud moves up, precipitation along the way removes more ^{18}O from the cloud. The cloud gets lighter when it gets to the higher latitude. Therefore, the polar region waters are richer in ^{16}O. If the precipitation comes from clouds in the south, it tends to be heavier; if the precipitation comes from clouds in the north, it tends to be lighter. Therefore, the points on the local MWL are scattered along the line. The slope of the line is due to further fractionation during precipitation. Local MWL for all three sites were established with the available precipitation data.

When plotting surface water isotopic signatures on the MWL, the dots that plot onto the evaporation line to the right of the MWL (Figure 2-2) represent residual water after evaporation. The further along the line it plots, more evaporation was expected to have occurred.

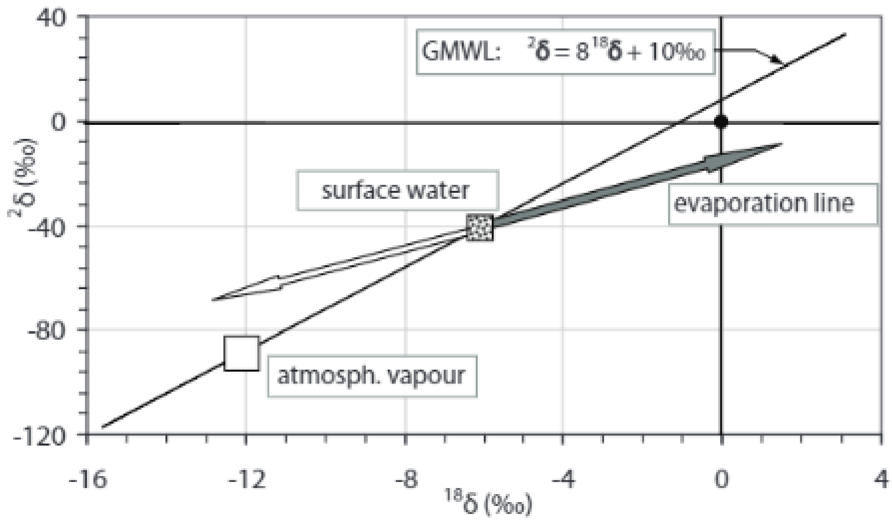


Figure 2- 2. Global meteoric water line (GMWL). Relation between the (δ18O, δ2H) values of meteoric water which undergoes evaporation, the vapor leaving the water and the residual water following evaporation, described by the evaporation line, compared with the relationship between atmospheric water and precipitation described by the meteoric water line. The relatively "light" (depleted) water vapor leaves the water reservoir (open arrow) causing the residual water to become enriched (grey arrow) (Mook, 2001)

2.3.3. Hydrograph Separation

Mass balance/hydrograph separation with isotopes dates back to late 1960s (Klans & McDonnell, 2013, Hubert et al., 1969; Crouzet et al., 1970; Dincer et al., 1970; Martinec et al., 1974; Martinec, 1975). Five assumptions were refined by Moore (1989) and Buttle (1994):

> "1) The isotopic content of the [precipitation] event and the pre-event water are significantly different; 2) The event water maintains a constant isotopic signature in space and time, or any variations can be accounted for; 3) The isotopic signature of the pre-event water is constant in space and time, or any variations can be accounted for; 4) Contributions from the vadose zone must be similar to that of groundwater; 5) Surface storage contributes minimally to the streamflow." (Klans & McDonnell, 2013)

A mass balance hydrograph separation model can be a two-component model or a three/multiple-component model (Kendall & McDonnell, 1999). The two-component model separates the pre-event component and the rainfall input component. Two-component models use the idea of mass balance in standard mixing conditions and equals the amount of a certain stable isotope (concentration * volume) before and after the event, thus partitioning the stream hydrograph into pre-event and rainfall components. For three or multi-component hydrograph separation, a tracer is needed, or a measurement of one-flow component is required (Klaus & McDonnell, 2013). One of the challenges is the accurate identification of end-members, as this will influence the calculated event/pre-event water fractions (Klaus & McDonnell, 2013). Groundwater, soil water, precipitation, and stormwater may all have a contribution to the flow samples. Among which, snow and rain on snow will further complicate the condition. The choice of using D or ^{18}O can create differences in separation results, which is the difference in estimated source fractions due to the effect of evaporated soil water and its differential impact on D and ^{18}O. Although challenge exists, using oxygen and hydrogen isotopes is ideal for hydrograph separation models because they are naturally added in precipitation events and are only going to change due to mixing once free from evaporative exposure (Kendall & McDonnell, 1998).

The expression provided in *Isotope Tracers in Catchment Hydrology* (Kendall & McDonnell, 1999) was given by Pinder and Jones (1969) and Dincer et al. (1970). It was adopted by Sklash et al. (1976) and Kennedy et al. (1986).

$$\delta D_E V_E = \delta D_{PW} V_{PW} + \delta D_R V_R \tag{3}$$

In the equation, D represents deuterium and V represents volume. Subscript E represents the total runoff due to the precipitation event; PW represents pre-event and R represents newly added water. In Kendall & McDonnell (1999), the above equation is combined with the mass balance among the three components: total runoff equals the sum of the other two, and the previous equation becomes the following equation.

$$V_{PW} = \left[\frac{\delta D_E - \delta D_R}{\delta D_{PW} - \delta D_R}\right] V_E \qquad (4)$$

Hydrograph separation method has been used in agricultural settings. Rozemeijer et al. (2010) calculated that the tile drain contribution to the total ditch discharge decreased from 80% to 28% in response to a rainfall event. Tomer et al., (2010) concluded that 68.6% of annual outflow came from tile drain and compared to SWAT prediction of 71%, confirmed the validity of the method.

2.3.4. Sensitivity Analysis

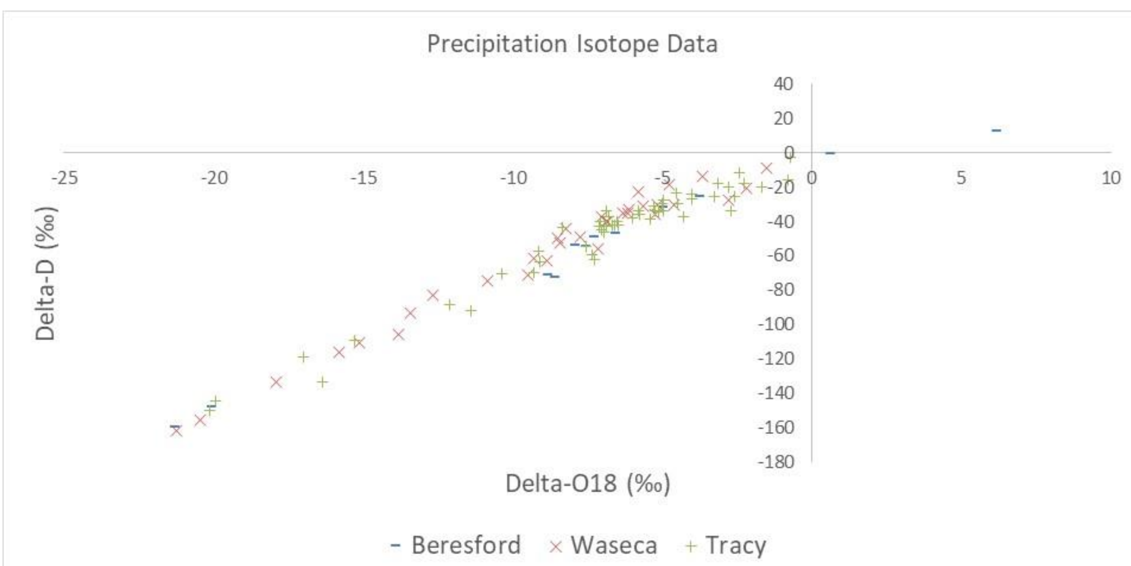
Due to data availability, limitations and uncertainties were associated with the hydrograph separation analysis. The samples collected were at fixed locations on a monthly basis. However, this was not representative of the entire watershed temporally and spatially. Each drain tile in the watershed receives water that moved through different landscape and soil profile. Varying evaporation and condensation conditions results in different isotopic signatures for tile waters. To investigate the reliability of the model, sensitivity analysis was performed.

For each site, each input parameter (source water δD and $\delta^{18}O$) was increased or decreased individually where other inputs were held the same. The corresponding output of tile water fraction in percentage was plotted against percent change in input parameters. The curves visually represent the magnitude of impact of each input parameter.

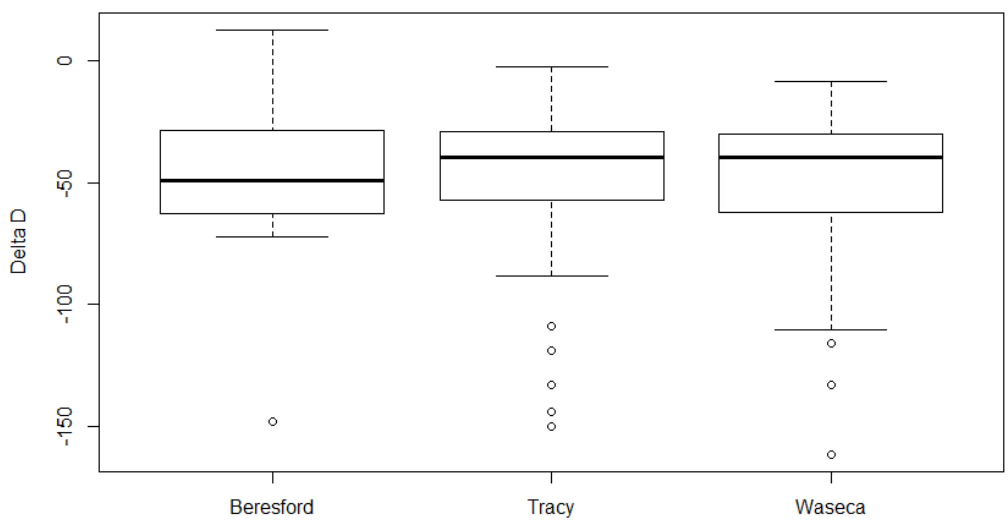
2.4. Results

Average annual rainfall during the sampling years (2016 and 2017) for Beresford was 79 cm, Tracy was 87 cm, and Waseca was 115 cm. Comparing isotopic signature of precipitation will help understand the source of the cloud and explain the isotopic signature of the other sampling locations.

A scatter plot was created for precipitation data from all three sites (Figure 2-3a) for direct visual comparison. Tracy and Waseca data plotted within the same range and Beresford plotted further into the first quadrant. Boxplots were also created for both δD and $\delta^{18}O$ (Figure 2-3b and 2-3c) of the precipitation samples. Both boxplots show that Tracy and Waseca had similar δD and $\delta^{18}O$ distribution, meaning that the precipitation cloud had similar evaporative signature, possibly from the same source. Precipitation clouds at Beresford showed a relatively heavier isotopic signature. It's likely that more of the clouds came from a lower latitude. This is explained by the rainout effect that as clouds move up latitude, precipitation condensation removes heavier isotopes and leaves the clouds lighter (Hoefs, 1997; Coplen et al. 2000).



(a)



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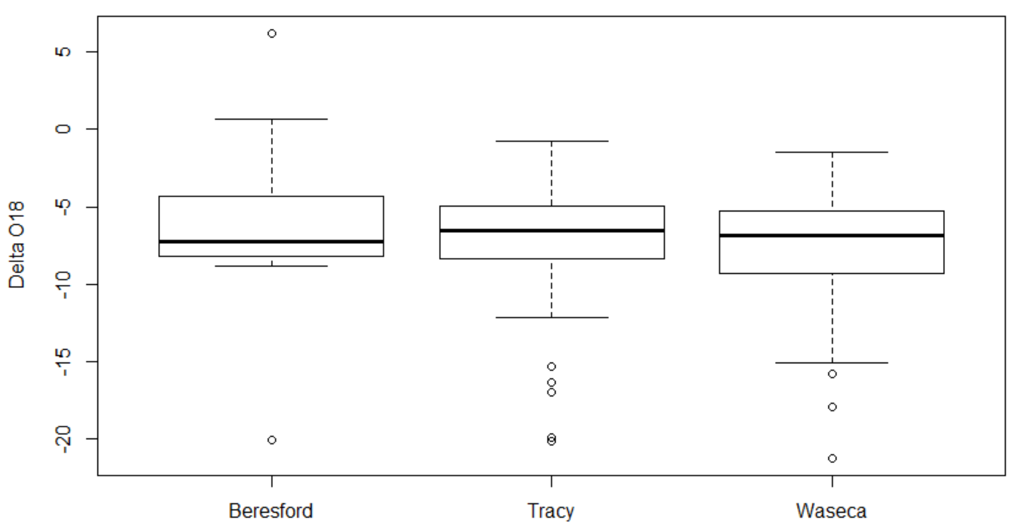


(c)

Figure 2- 3. Precipitation isotopic signature plots. (a) 2016-2017 isotopic signature plots from Beresford, Tracy, and Waseca; (b) Boxplot for Delta D from three site using 2016 and 2017 daily precipitation data; (c) Boxplot for Delta O18 from three site using 2016 and 2017 daily precipitation data

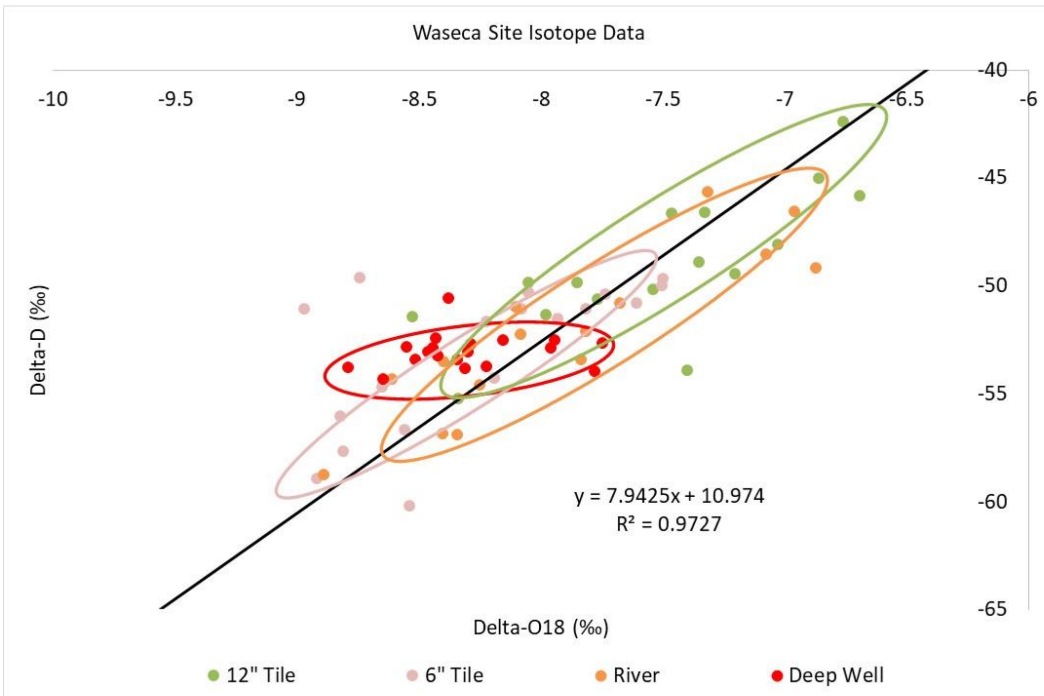
2.4.1 Meteoric Water Line

Local meteoric water lines (LMWL) were established for all three sites (Figure 2-4). The meteoric water line takes the form of equation as below and Table 2-2 summarized the intercept and slope of each site.

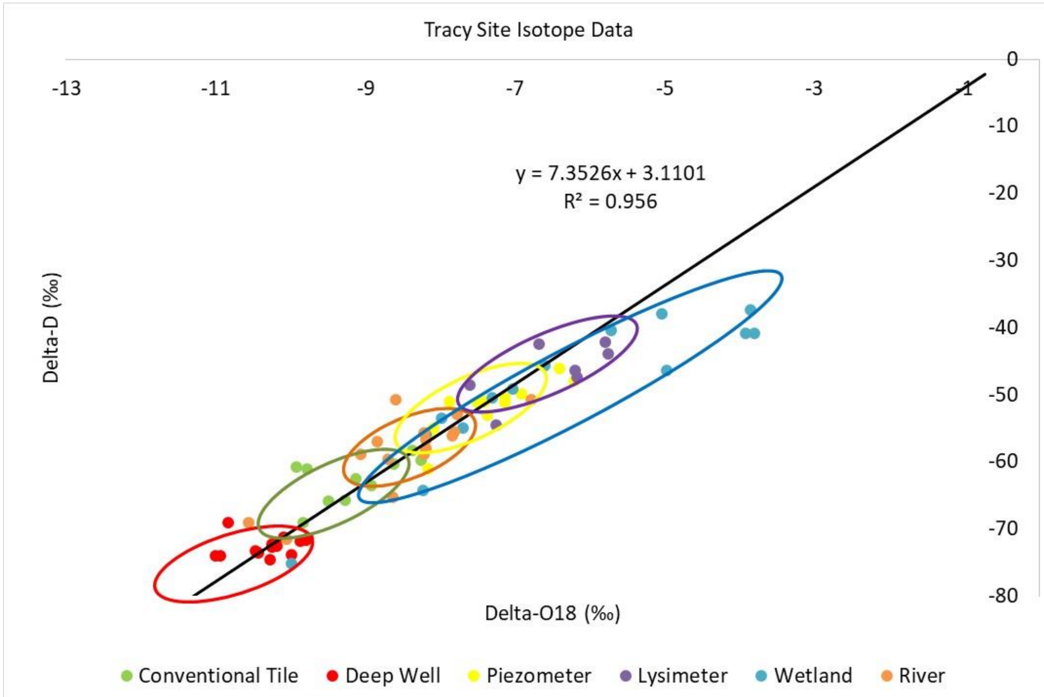
$$y = ax + b \tag{12}$$

Table 2- 2. Parameters of meteoric water lines

Site	Slope (a)	Intercept (b)
GMWL	8	10
Waseca LMWL	7.94	10.97
Tracy LMWL	7.35	3.11
Beresford LMWL	6.38	-9.46



(a)



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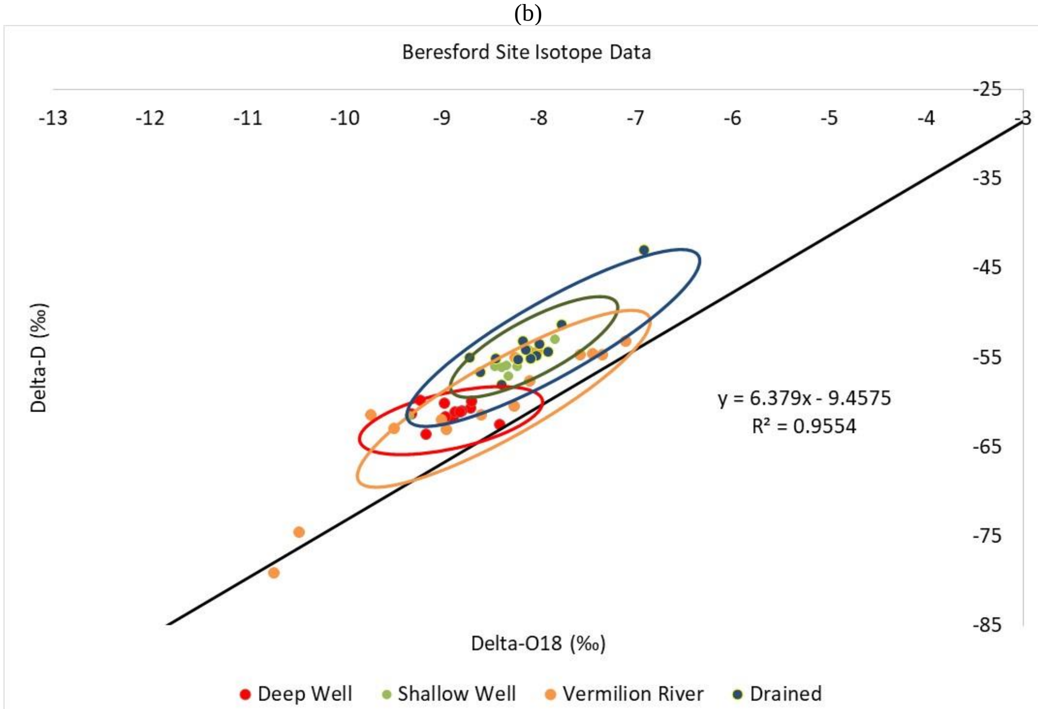


(c)

Figure 2- 4. LMWL and water sample isotope plots for each site. (a) is Waseca site; (b) is Tracy site; (c) is Beresford site

Among the three sites, Tracy site data is the most deviated. The differences between sampling locations are very well demonstrated on the Figure 2-4 (b). Wetland and deep well data lie on the opposite ends of the plot. They show the most difference in isotopic composition. The wetland water has a lot more evaporative signature than the rest of the locations, which is true for evaporation surface water experiences. The wetland water isotopic signature ranged from deep well to evaporative water. It's likely that the wetland receives groundwater input to sustain the long-term standing water table. Deep well water has the least evaporative signature, and this agrees with the field condition.

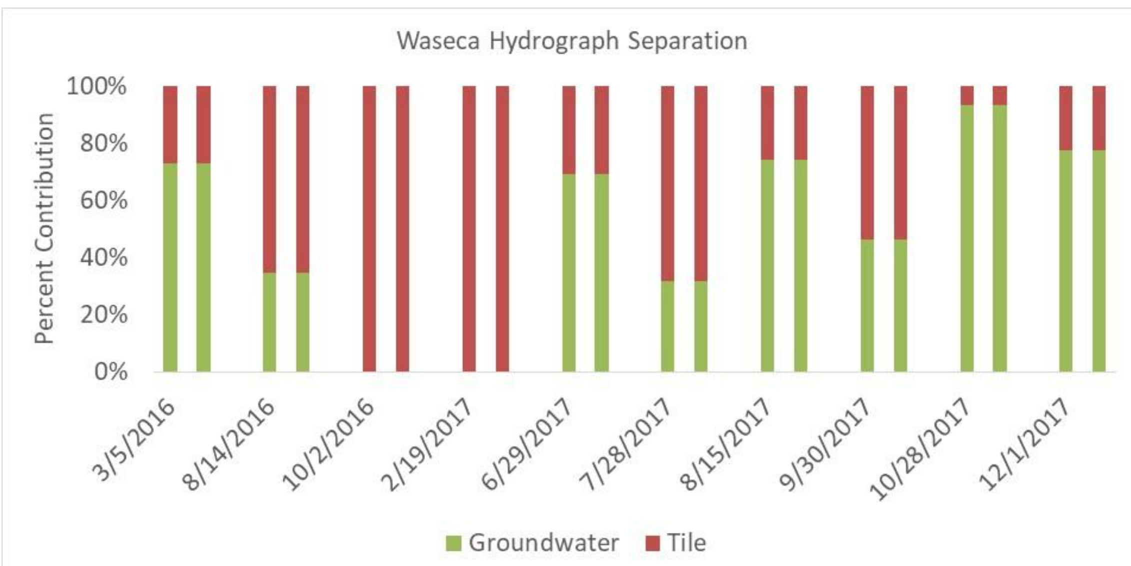
Waseca and Beresford sites have the data points plotted closer together. Field investigation suggested that at Waseca site, the 6" tile conveys shallow groundwater. Therefore, it is not surprising that the isotopic signatures from the 6" tile is similar to that from the deep well. River and drain tile both had certain level of evaporation with drain tile water having a little more evaporative signature. Deep well and the 6" tile isotopic signatures intercept with all the other locations. Groundwater isotope signature has a presence at all other locations. Compare to Tracy site, groundwater has a larger impact on the watershed hydrologic characteristics.

Beresford had almost all the water samples plot above the LMWL. This is not commonly seen, but it's not impossible. Literatures suggest that this phenomenon happens in low humidity regions when re-evaporation of precipitation increased water vapor masses with even lighter isotopic composition (Kong et al., 2014; Chen et al., 2006). Groundwater also appeared to have a significant impact in this watershed.

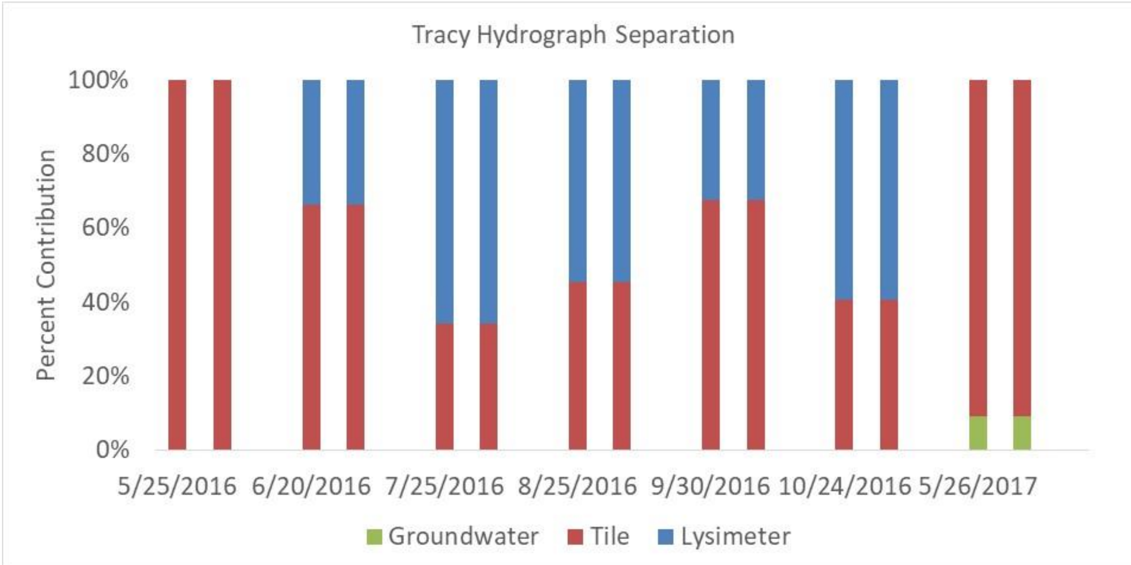
2.4.2 Hydrograph Separation

The two-component hydrograph separation model was applied to all three sites. The number of end members can be solved is limited by the number of variables measured due to mathematical limitation. The results are shown in Figure 2-5. Uncertainty existed in the two-component model, which was quantified using sensitivity analysis. River sampling locations were chosen to be far away from the tile outfall and groundwater seepage points to minimize the impact of any partial mix. The analysis assumed that the streamflow was a well-mixed system.

Based on field observation, on days with no precipitation, tile flow and groundwater seepage were the major inputs to streamflow. Other minor inputs include surface runoff and soil water from a long-term scale. Tile flow isotopic signature was always used as one of the components when available at all three sites as the main purpose was to characterize tile flow contribution to streamflow. The dates were selected when streamflow, tile, and deep well (or wetland at Tracy site) were all available. No precipitation or major surface runoff was observed on selected days.



(a)



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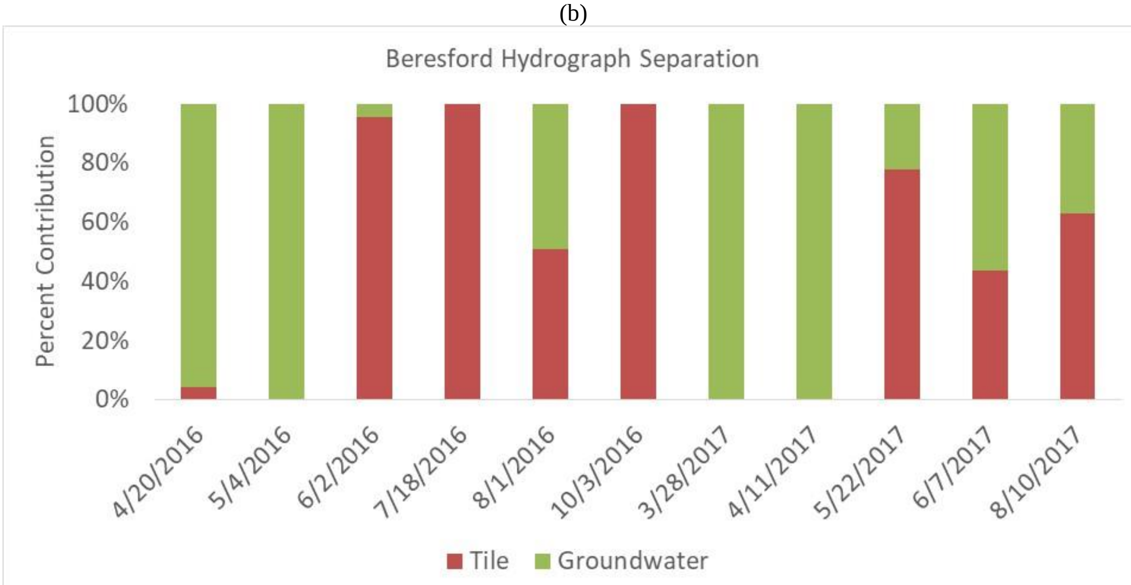


(c)

Figure 2- 5. Two-component hydrograph separation for the three sites. GW stands for groundwater. The y-axis is the ratio of component assuming total volume is one. (a) is Waseca site; (b) is Tracy site; (c) is Beresford site for Vermillion River

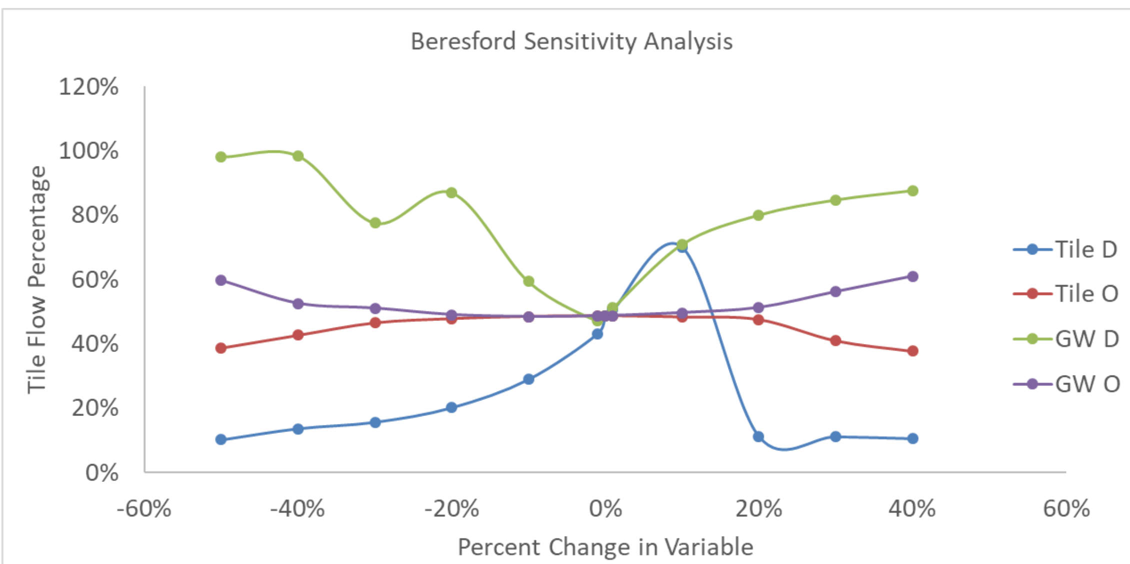
At Tracy site, lysimeter isotopic signatures were used to represent soil water component based on the interpretation of LMWL in Figure 2-4b. First attempt was to not include soil water and try to partition out groundwater and tile flow. However, most of the days, river water had an isotopic signature lighter than both sources (Figure 2-4b), where soil water became one of the components. On days when groundwater had a more significant impact on streamflow, it was around 9%. However, tile water was responsible for more than 60% of the streamflow on days it was measured. This should not be interpreted as an annual average as tile flow rate varied from day to day including no flow.

At Waseca and Beresford sites, no water samples representing surface runoff or soil water was taken. Therefore, only groundwater and tile flow were used as the components. Both locations agreed with the LMWL plot that groundwater had a bigger impact on streamflow than Tracy. Waseca groundwater had an average of 50% contribution to streamflow on days measured in 2016 and 2017, Vermillion River 51%. Correspondingly, Waseca tile impact is 50% and 49% for Vermillion River. Overall, all three sites streamflow isotopic signature was greatly driven by tile flow.

2.5. Discussion

One of the major factors that limited this analysis was the number of variables. As discussed in previous section, the number of components was governed by the number of variables measured. Two variables (δD and $\delta^{18}O$) meant two components. However, considering the complexity of the system, where streamflow receives major inputs from groundwater, tile flow, overland runoff, shallow subsurface water, and direct precipitation, only being able to include two of these skewed the result. This explains why in Waseca, there were days where groundwater input did not exist. Mathematically speaking, if streamflow isotopic signatures are a result of the mixing, the streamflow isotopic number should be in between the two sources. However, if the two sources are both greater or less than the streamflow isotopic number, this causes one source to dominate. In reality, another source will contribute to the streamflow to balance out the mixing and this was not represented in the two-component model.

Evaluating the robustness of the system improved the understanding of the uncertainty of the analysis. Sensitivity analysis was applied on all three sites and presented visually in graphs below (Figure 2-6). Each variable changed was listed in the legend of each graph where O represents $\delta^{18}O$ and D represents δD. All three graphs indicated the same pattern where changes in δD had very little impact on the estimated tile flow proportion. Whereas a small change in $\delta^{18}O$ resulted in a big shift in the estimated tile flow contribution to streamflow. The confidence of the model is limited by the accuracy of $\delta^{18}O$ sampling and analysis.



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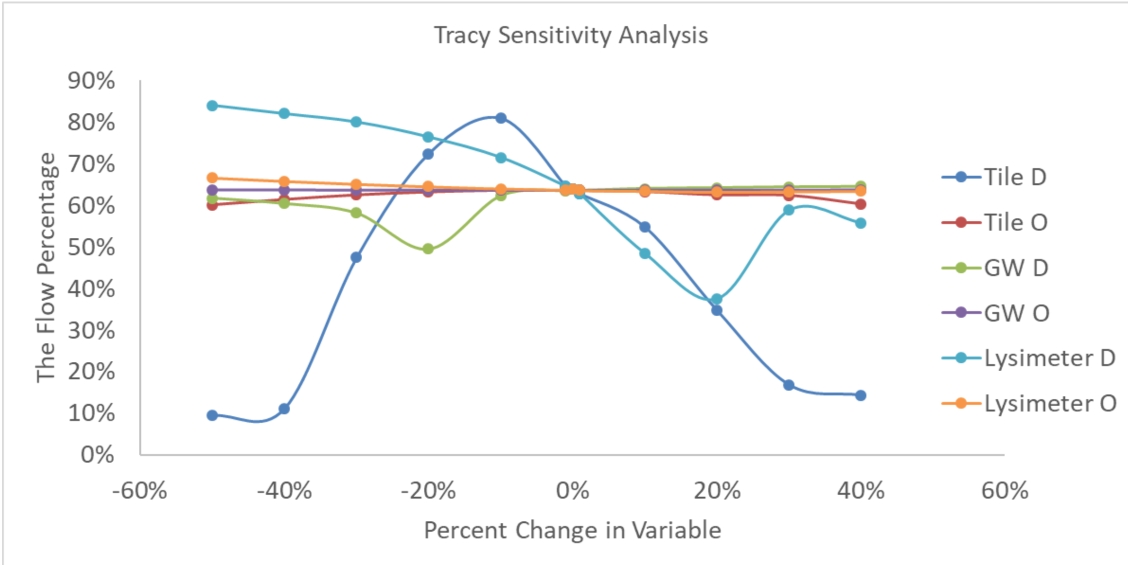

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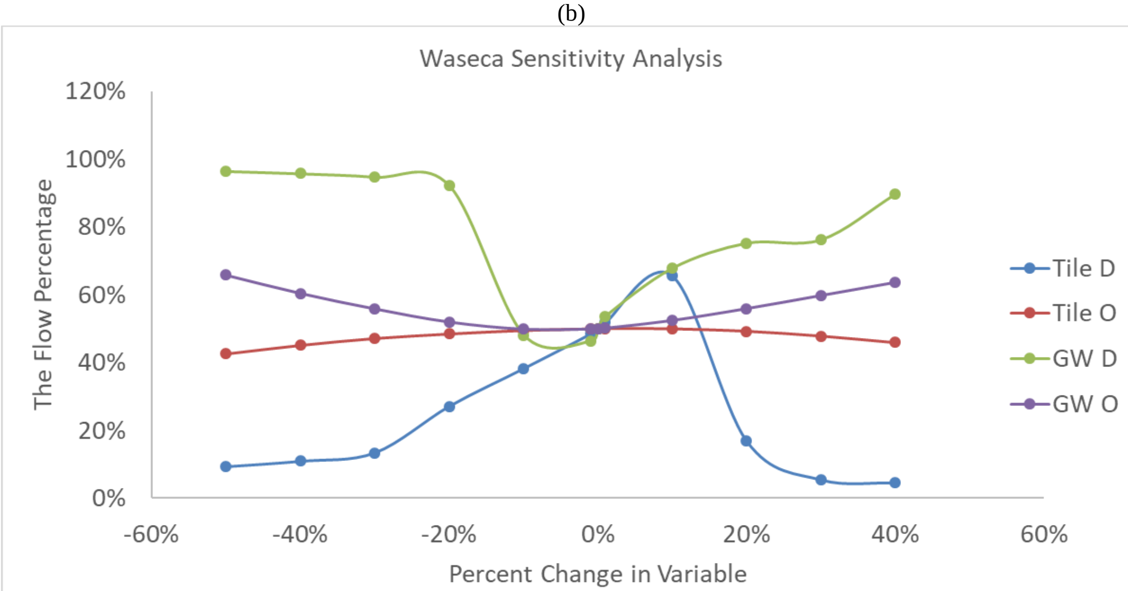

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Figure 2- 6. Sensitivity analysis where each variable was changed and the change in estimated tile flow percentage was compared

2.6. Conclusion

Hydrograph separation analysis can be used to help better quantify the contribution of different sources to the receiving water. This knowledge is extremely helpful in farm practice selection or watershed planning.

Water stable isotopes are especially used in situation where chemical fate and transport happens in the process. The current assumptions include a well-mixed system and representative sampled water. The assumption of well-mixed system is typically true for stream systems if samples are not taken at mixing spots. However, taking representative samples can be difficult because the stream system receives numerous tile and ditch outfalls. Tiles located in different area conveys water of different isotopic signature due to the local preferential flow path and groundwater stage. The sampled tile is likely to have a different characteristic from the others. Therefore, the analysis is most useful in investigating the local hydrology rather than watershed-wide mixing mechanism. More samples from different locations will be required to better perform hydrograph separation analysis on a watershed scale.

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3. Analysis of Mean Transit Time of Water in Tile-Drained Agricultural Landscape Using Stable Isotopes

3.1. Preface

Agricultural activities have greatly altered the hydrology in the landscape. Tile drains changed how and when water is discharged into the streams. Stable isotopes of oxygen (oxygen-18) and hydrogen (deuterium) were used to investigate the mean transit time of water through a tile-drained landscape. Monthly hydrogen and oxygen stable isotope samples were collected at the three research fields: Waseca, MN, Tracy, MN, Beresford, SD and in 2016 and 2017. Lumped parameter modeling approach was applied to each data set to investigate the mean transit time of water through different depths of the field, such as groundwater and tile. This study found that precipitation water took an average of 9 months to move through different pathways and gain groundwater isotopic signature and an average of 4 months to gain tile water signature.

3.2. Introduction

Cottonwood, Le Sueur River Watershed in Minnesota and Vermillion River Watershed in South Dakota are all agricultural watersheds. Cropland accounts for 84% of the land use within the Cottonwood River Watershed (MPCA, Minnesota River-Cottonwood River Watershed); 82% for Le Sueur River Watershed (Le Sueur River WRAPS Report); and 67% for Vermillion River Watershed (Vermillion River Basin Watershed Implementation Project Segment 1).

Extensive drain tile system implementation altered the local hydrology by allowing subsurface water discharge faster into the receiving water (Sheler, 2013). Increased stream peak flow can cause negative downstream impacts such as flooding and increased streambank erosion. Less holding time of water in the soil profile also allows more nutrients into the surface water as the hydraulic residence time (HRT) limits the biological removal processes in the soil. Increasing soil water holding is important for the three sites as Cottonwood River was listed on 303(d) as impaired for turbidity and Le Sueur River was listed as impaired for excess nutrient. Vermillion River was impaired for TSS as indicated by the Vermillion River Strategic Plan (2013).

One of the most important factors for excess nutrient export from tile drained system is hydraulic residence time (Schipper et al., 2010; Saito et al., 2013). Drain tiles reduce the time water stays in the soil and thus limiting the ability of soil microbes in removing contaminants. Agricultural best management practices (BMP) such as bioreactor, saturated buffer, controlled drainage, water and sediment control basin (WASCOB), etc., are designed to prolong the residence time of water in the landscape for increased contaminant removal. Understanding how long water takes to move from land surface to other parts of the field can fill in the gaps of water balance analysis and provide additional information on how water balance can be adjusted under different scenarios such as climate change and BMP implementations.

Stable oxygen and hydrogen isotopes have been used in water science related research to help understand HRT/mean transit time (MTT) of water (Kirchner, 2015; McGuire et al., 2002; Mensah et al., 2014). The two terms are usually not very well distinguished in the literature and they have been used interchangeably (McGuire & McDonnell, 2006). The two terms represent different processes in a catchment system.

Hydraulic residence time is defined as the length of time a molecule spends in a catchment system from entry (Maloszewski & Zuber, 1982). Transit time is the time that it takes a molecule to exit the catchment system (Bolin & Rodhe, 1973; Etcheverry & Perrochet, 2000; Rueda et al., 2006). For example, in soil water storage, water molecules that are retained in the soil have a longer residence time than water that drained out. This is accounted for conceptually in the mean HRT, but not MTT as it does not exit the system. However, these two terms are also highly related. Transit time of water through a system depends highly on the hydraulic pathway within the system itself. A longer transit time may indicate longer residence time. Therefore, investigating MTT will give an indication of HRT and thus reflect on the water quality benefit of the system.

Literature introduced different approaches to estimate MTT (McGuire & McDonnell, 2006). Convolution integral with lumped parameter mathematically describes the transport of conservative tracers through a watershed. Figure 3-1 explains the theoretical approach of lumped parameter analysis. As shown in the figure, precipitation adds water that contains a certain level of oxygen and hydrogen tracers to the catchment. The precipitation water makes its way to the stream network through different pathways like surface runoff, unsaturated zone drainage, and saturate zone seepage, resulting in a damped and lagged outflow signature. The convolution integral takes the form as Equation 1:

$$\delta_S(t) = \int_0^\infty TTD(\tau)\delta_P(t-\tau)d\tau \quad (1)$$

Where:

τ is the lag time between precipitation and streamflow isotopic composition, therefore, $(t-\tau)$ is the time of entry into the system;

$\delta_S(t)$ is the lagged response of isotopic signal of receiving water (streamflow);

$\delta_P(t-\tau)$ is the isotopic signal of precipitation;

and $TTD(\tau)$ is the distribution of water travel time.

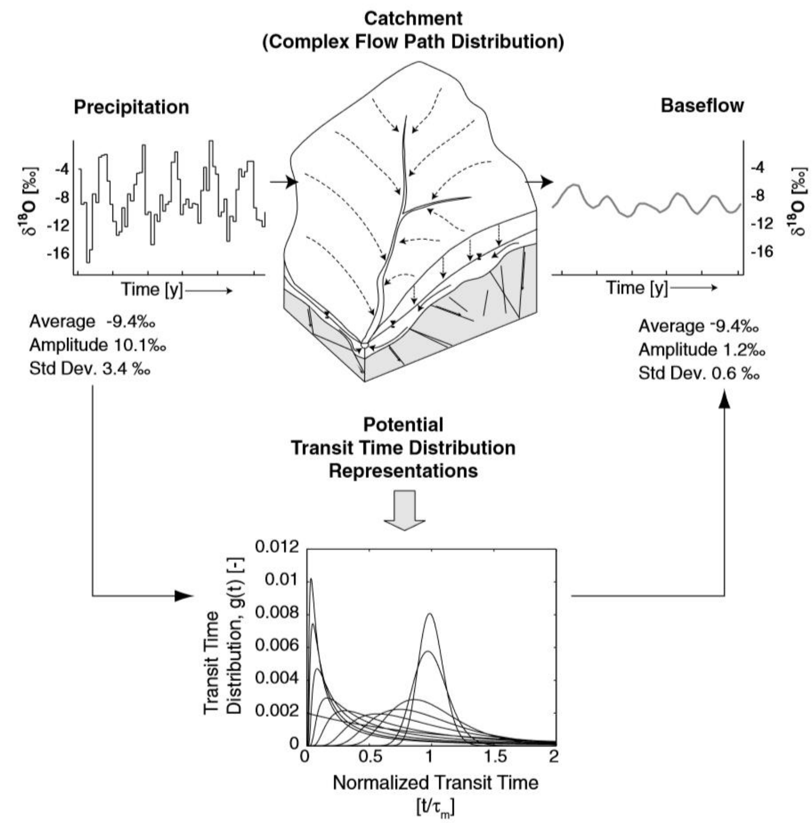


Figure 3- 1. Conceptual diagram of the lumped parameter transit time modeling approach (Plummer et al., 2001; McGuire & McDonnell, 2006)

Travel time distribution (TTD) takes various shapes depending on the flow path and mixing mechanisms. These include, but not limited to, piston flow, exponential flow, dispersion flow, etc. (Maloszewski et al., 1983; Stewart & McDonnell, 1991; Hrachowitz et al., 2009; Vitvar & Balderer, 1997; McGuire et al., 2002; McGlynn et al., 2003; McGuire et al., 2005; Tetzlaff et al., 2007).

Lumped parameter approach has been widely used by researchers, with different tracers, to estimate water travel time. Maloszewski & Zuber (1982) test the models by reinterpreting several known case studies. The model distributions tested were piston flow model, exponential flow model, combined exponential and piston flow model, linear model, combined linear and piston flow model, finite state mixing model, and dispersive model. The authors concluded that exponential-piston flow and dispersive model gave better fitting result than the other simpler models. This is mostly true for natural systems as the soil matrix is usually not uniform and plant root system adds more complexity to it. Same conclusion can be inferred for most natural systems.

Hrachowitz et al. (2009) used chloride as the conservative tracer to study transit times of two small (~ 1 km^2) watersheds using lumped parameter approach. Weekly chloride concentration in precipitation and streamflow was collected for 8 years and corrected for evaporation. The authors used exponential flow, exponential piston flow, diffusion/dispersion, gamma models, as well as sine wave model. They concluded that the shorter MTT helps to fully recover the tracers and increases confidence in the feasibility of the travel time distributions and the validity of the assumptions (Hrachowitz et al., 2009; McGuire et al., 2005).

Common simplification of this lumped parameter model takes advantage of the season variation of isotopic composition and can be represented with a sine-wave model. However, this model does not allow variation of different flow types (McGuire & McDonell, 2006).

When plotted against time, isotopic signatures of both the annual precipitation and surface water appeared to take the shape of a full sine curve. Assuming the waters represent a steady-state, well-mixed reservoir, amplitude value was extracted from both curves and used in the following equation:

$$T = \omega^{-1}\left[\left(\frac{A}{B}\right)^2 - 1\right]^{\frac{1}{2}} \tag{2}$$

Where:

T is the residence time (days);

ω is the angular frequency of variation (2π/365 days);

A is the input (precipitation) amplitude;

B is the output (surface water) amplitude.

On the days where precipitation does not occur, or precipitation sample is not available, the isotopic signature can be calculated using the following equation (Yurtserver, 1975):

$$\delta^{18}O = (0.521 \pm 0.014) * T(C) - (14.96 \pm 0.21) \tag{3}$$

Where:

$T(C)$ is temperature of the day.

This equation represents a linear relationship between temperature and O^{18} abundance. Local linear relationships can be developed with local temperature and precipitation isotopic data in order to have a more accurate estimate.

Burns & McDonnell (1998), in their paper, used the sine-wave model to estimate stream water, groundwater, and soil water residence times based on annual isotope signature from surface water and meteoric water to investigate impacts of a beaver pond on runoff processes. They measured ^{18}O monthly from June 1989 to December 1990. The term mean residence time was used. The residence time in this model was defined as the average time that "elapses between parcels of water entering as precipitation and leaving again as streamflow" (Kirchner, 2015), which is the same as MTT. A longer MTT indicates greater damping of seasonal tracer cycles. Therefore, the amplitude of a seasonal tracer is used for such model (Kirchner, 2015). The model produced reasonable results and helped authors conclude that beaver pond had no significant influence on baseflow.

However, the use of stable isotope is not perfect. In Stewart et al. (2010), the authors pointed out the potential issues with the model. By only using stable isotopes, the estimated stream residence time is truncated. "When tritium is used, the age distributions generally have long tails showing that groundwater contributes strongly to many streams, and consequently that the streams access considerably larger volumes of water in their catchments than would be expected from stable isotope data use alone" (Stewart et al., 2010). The authors provided a comparison between residence times calculated with only stable isotopes and tritium (Table 3-1).

Table 3- 1. Summary of the examples of the difference between 18O- and 3H- based mean transit times (Stewart et al., 2010)

Catchment	Flow components			Blackbox MTTs (year)	
	Type	MTT (year)	%	$^{18}O/^{2}H$	^{3}H
Lainbach Valley[b]	Surface runoff	~0·01	30	*All flow* 1·1 (1·1[a])	1·8 (1·7[a])
	Upper reservoir	0·8	52·5	*Subsurface flow*	2·3 (2·5[a])
	Lower reservoir	7·5	17·5	2·1 (1·6[a])	
Brugga Basin[c]	Event water	~0·01	11·1	*All flow* 2 · 6[a]	3·3[a]
	Shallow groundwater	2·3–3	69·4	*Subsurface flow*	3·7[a]
	Deep groundwater	6–9	19·5	2·9[a]	
Pukemanga Catchment[d]	Direct runoff	~0·1	15	*All flow* 3·4[a]	9·0[a]
	Groundwater	10·6	85	*Subsurface flow* 4	10·6
Waikoropupu Spring[e]	Shallow groundwater	1·2	26	*Subsurface flow*	7·9 (7·9[a])
	Deep groundwater	10·2	74	2·6–3·9 (3·3[a])	

[a] Calculated by combining the flow components in the indicated proportions.
[b] Maloszewski *et al*. (1983).
[c] Uhlenbrook *et al*. (2002a)
[d] Stewart *et al*. (2007)
[e] Stewart and Thomas (2008).

The first study treated the whole system as a black box and only focused on the "in" and "out" isotope concentrations (Maloszewski et al., 1983). The second study had 70% of the flow went through a subsurface reservoir (Uhlenbrook et al., 2002). The third study separated the subsurface reservoir into upper reservoir with shorter turnover time and lower reservoir with longer turnover time (Stewart et al., 2007). The last study treated the whole system as a black box and studied the sources flowing into a spring (Stewart & Thomas, 2008). From the four examples, the use of tritium in residence time calculations increased the estimated residence time. This deviation agrees with Kirchner (2015) who suggested that the use of seasonal cycles of stable isotopes (chloride, ^{18}O, or D) accurately predicts the young water fraction, but not the mean residence time.

The question this study seeks to answer is how tile drain system affects local field level hydrology. To further explore the impacts, stable isotope tracers were used as conservative tracers for lumped parameter analysis to estimate MTT at different hydrologic cycle components.

3.3. Sampling and Method

3.3.1. Sampling

Deuterium (D) and oxygen-18 (^{18}O) were used in this study. Deuterium is one of the two stable isotopes of hydrogen. Tritium, the heaviest hydrogen isotope, is also radioactive. The half-life of tritium is 12.3 years. Oxygen has three isotopes as well: ^{16}O, ^{17}O, and ^{18}O. All three isotopes are stable. Vienna Standard Mean Ocean Water (VSMOW) is a universal standard set by International Atomic Energy Agency (IAEA) for comparison of heavy isotopes as they are usually in trace amount. IAEA defines δD and $\delta^{18}O$ as the following:

$$\delta D\ (‰) = \left(\frac{R_{sample}}{R_{VSMOW}} - 1\right) * 1000 \tag{4}$$

$$\delta^{18}O\ (‰) = \left(\frac{R_{sample}}{R_{VSMOW}} - 1\right) * 1000 \tag{5}$$

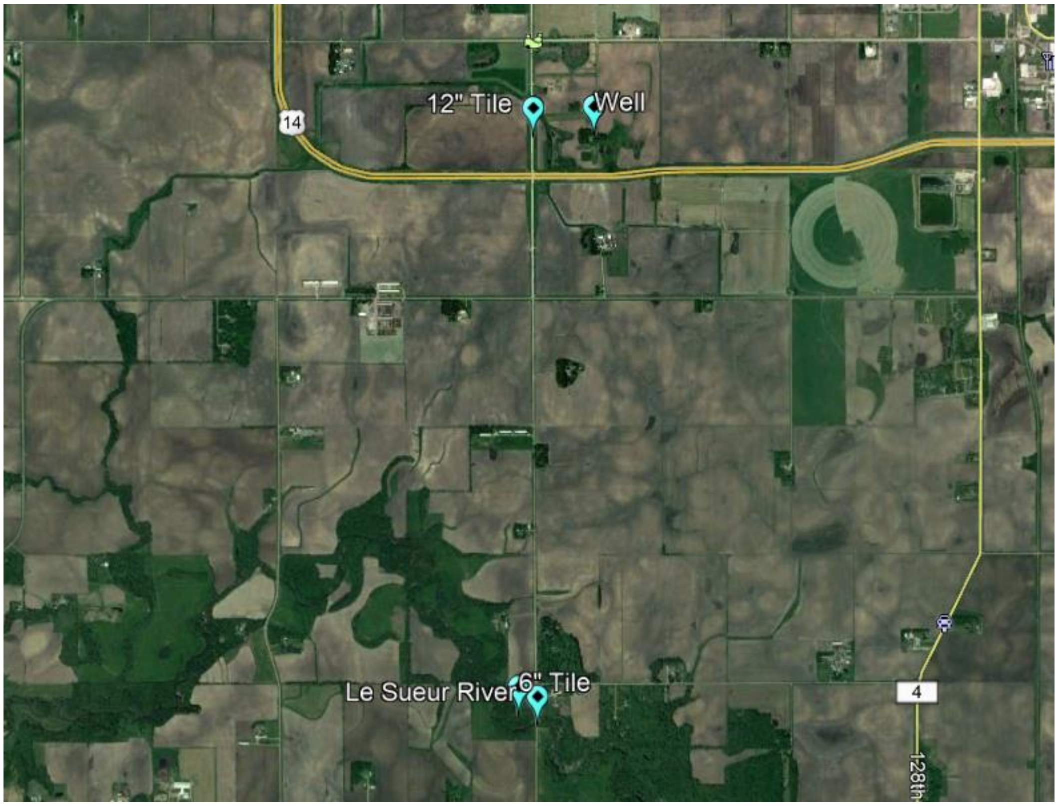
Where:

R equals to ${}^{2}_{1}H/{}^{1}_{1}H$ and ${}^{18}_{8}O/{}^{16}_{8}O$, respectively;

and δ represents the ratio.

Since the concentrations of the D and O^{18} isotopes are extremely small, the equations above use ratio to convert those small numbers into larger numbers for comparison purposes. This ratio is widely used in isotope studies.

Isotope samples were collected monthly from March 2016 to March 2018 from three locations: Beresford, SD in the Vermilion River Watershed, Tracy, MN in the Cottonwood River Watershed, and Waseca, MN in the Le Sueur River Watershed. Figure 3-2 shows the sampling locations at each site. Table 3-2 shows the depth of each sampling location. A bailer was used to sample the wells. The wells were bailed ten times before sampling to allow water to flow in.



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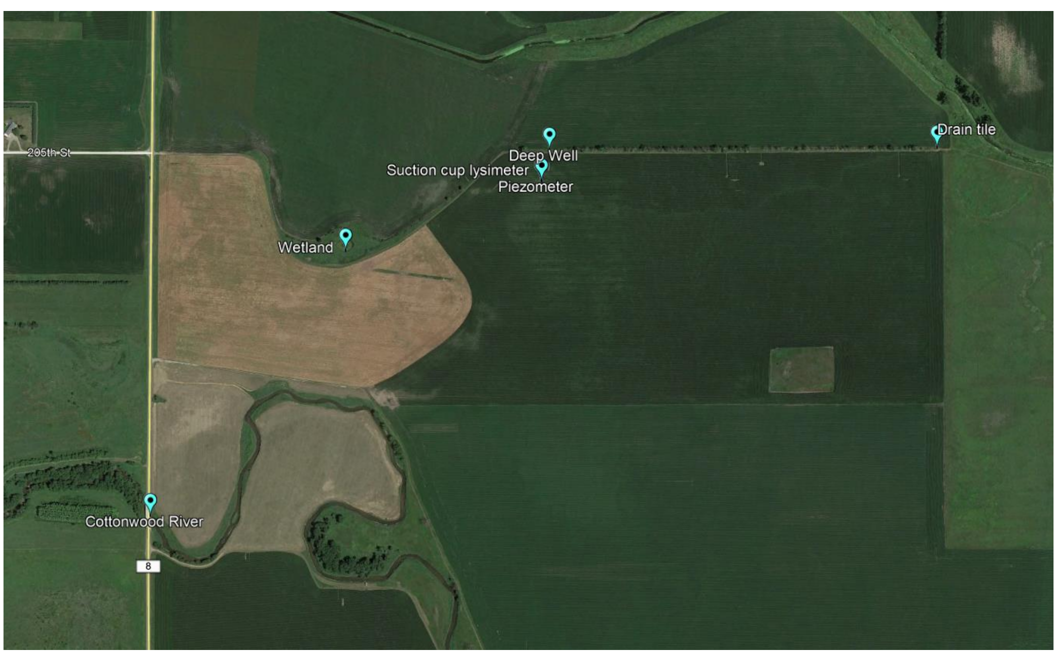

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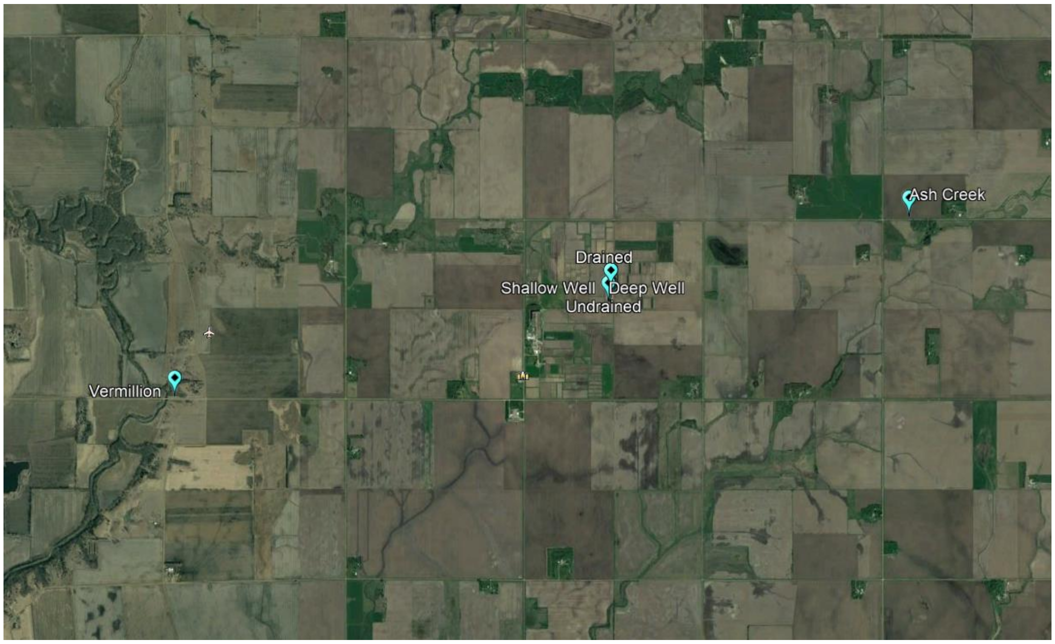


(c)

Figure 3- 2. Sampling locations at each site. (a) is Waseca; (b) is Tracy; (c) is Beresford

Table 3- 2. Subsurface sampling depth at each site (from shallow to depth)

Sampling Location	Waseca	Tracy	Beresford
Lysimeter	-	0.76 m	-
Drain tiles	1.2 m	1.2 m	1.2 m
Shallow well	-	-	1.5 m
Piezometer	-	2.4 m	-
Deep well	13.1 m	10.7 m	10.7 m

The university-level lab used laser spectroscopy system (Liquid Water Analyzer, DLT-100, Los Gatos Research, Inc) coupled to a PAL autosampler for simultaneous measurements of D/H and $^{18}O/^{16}O$. The precision of δD is ±1.0‰ and that of $\delta^{18}O$ is ±0.25‰. A standard was run after every two unknown samples to correct for any instrumental drift and errors (Xiao, 2015).

3.3.2. Mean Transit Time

Lumped parameter method was used for the MTT analysis (Equation 1). There are two main components in the equation: input function and TTD distribution.

Tile drain system promotes infiltration and reduces surface runoff, surface runoff contribution to streamflow is relatively small compared to shallow subsurface, tile, and groundwater. It is not appropriate to directly use precipitation ^{18}O as the input to Equation (1). Therefore, an input function, Equation (6), was necessary to adjust the precipitation ^{18}O to a more appropriate recharge water isotopic signature (Maloszewski et al., 1992; Bergmann et al., 1986).

$$\delta_s(t_i) = \frac{[N\alpha_i P_i(\delta_i - \delta_{GW})]}{\sum_{i=1}^{N}(\alpha_i P_i)} + \delta_{GW} \tag{6}$$

$$\alpha = [\textstyle\sum_w(P_i\delta_i) - \delta_{GW}\sum_w(P_i)]/[\delta_{GW}\sum_s(P_i) - \sum_s(P_i\delta_i)] \tag{7}$$

Where:

α is the infiltration coefficient;

i is the ith month;

N is number of years for which precipitation was collected;

P is total precipitation for the corresponding month;

w and s represent winter and summer corresponding.

This function assumes that recharge water, which is responsible for watershed turnover, has the same isotopic composition as model input water. Input function calculation is based on an infiltration coefficient, mean groundwater (assumed to be recharge water) ^{18}O composition and weighted summer/winter precipitation ^{18}O. Infiltration coefficient was calculated using average tile flow ^{18}O signature. In this paper, summer months assumed to be April to September and winter months assumed to be October to March.

Literatures suggest that Exponential-Piston-Flow model is suited for describing water transit time (Maloszewski and Zuber, 1982; McGuire et al., 2002). The TTD model selected in this research was Exponential-Piston-Flow (EPM) model. The model distribution is described by the following equation (Maloszewski and Zuber, 1982; McGuire et al., 2002; McGuire & McDonnell, 2006):

$$TTD(\tau) = \frac{\eta}{\tau m} \exp\left(-\frac{\eta\tau}{\tau m} + \eta - 1\right) \qquad for\ \tau \geq \tau m(1 - \eta^{-1})$$

$$TTD(\tau) = 0 \qquad for\ \tau \leq \tau m(1 - \eta^{-1}) \tag{8}$$

Where:

τm is the mean transit time;

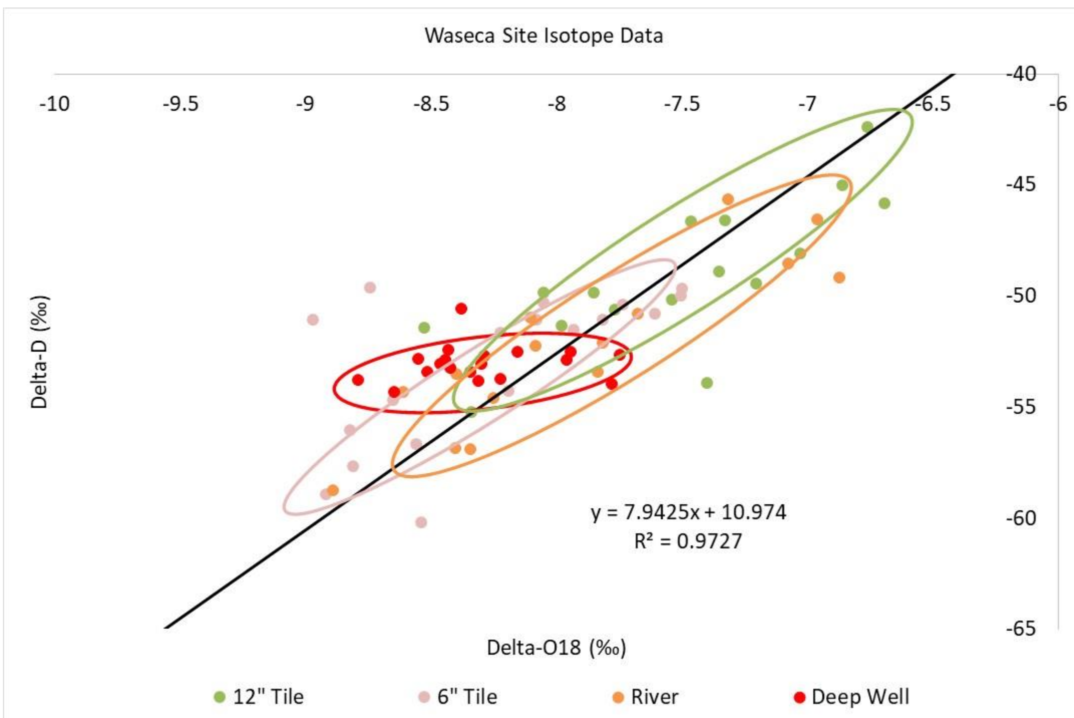
η is calculated as total volume/exponential volume, also as EPM ratio plus 1. EPM ratio is the ratio of the length of area at the water table not receiving recharge to the length of area receiving recharge

As mentioned above, different TTD distribution is caused by variation of the catchment flow pathway. Exponential-piston-flow model contains both piston flow and exponential flow features in the same catchment; where, piston-flow model assumes that the catchment has no hydrodynamic dispersion or mixing and has high linear flow velocity and exponential model describes flow pathway through a homogeneous and unconfined aquifer with constant thickness receiving uniform recharge.

Sine-wave model was also selected for this study, however, was biased due to sampling limitation. Under frozen condition, a few locations were not available for sampling. The tile also didn’t flow continuously. With the missing data, the amplitude of the output sine curves could be wrongly estimated, which would have a significant impact on MTT estimation.

3.4. Results

Local meteoric water lines and water sample plots were established for each site (Figure 3-3). The figures showed that at Waseca (Figure 3-3a) and Beresford (Figure 3-3c) sites, groundwater had a larger impact on local hydrology than Tracy (Figure 3-3b). Tracy groundwater isotopic signature was more separated from the rest of the water sources, unlike Waseca and Beresford.



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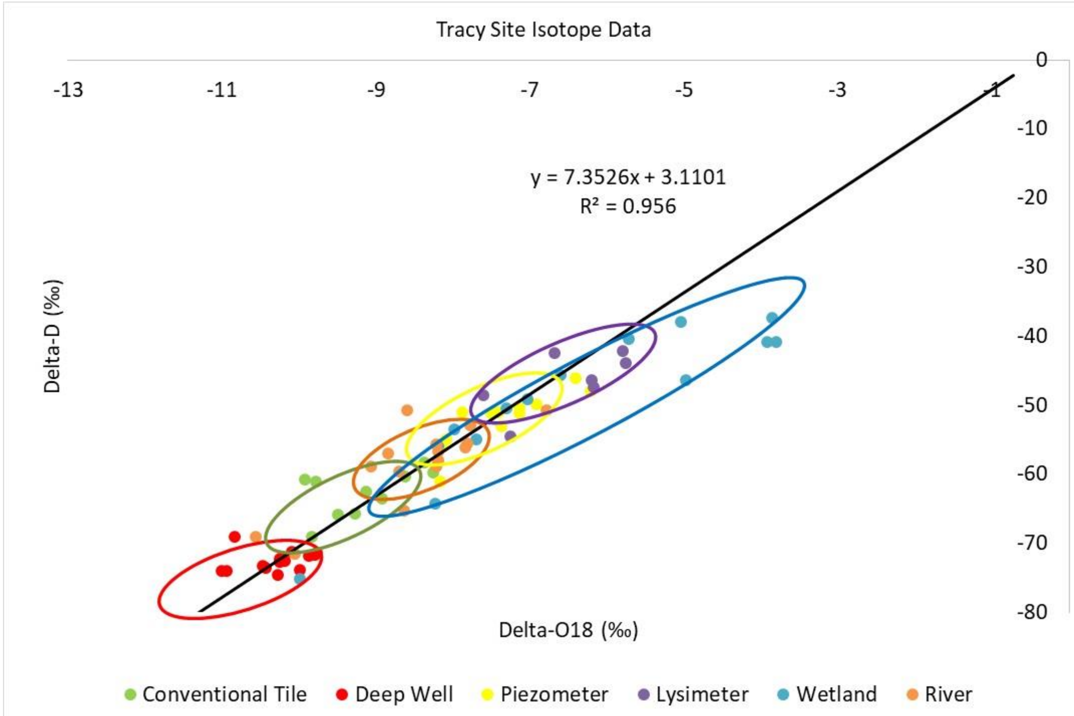

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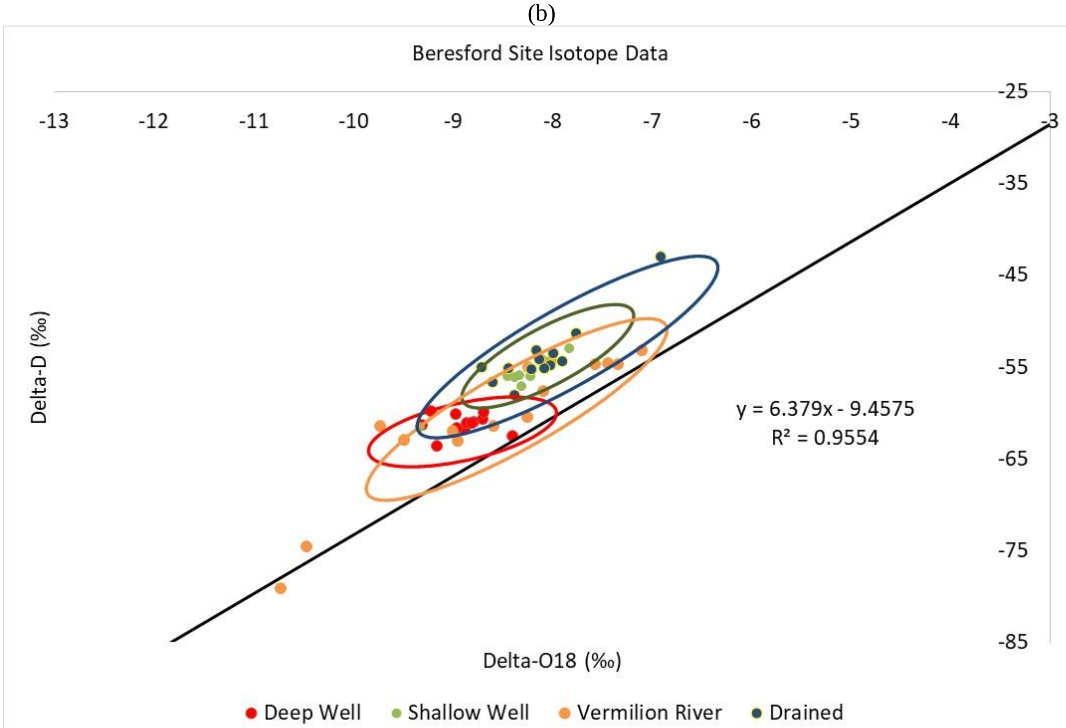
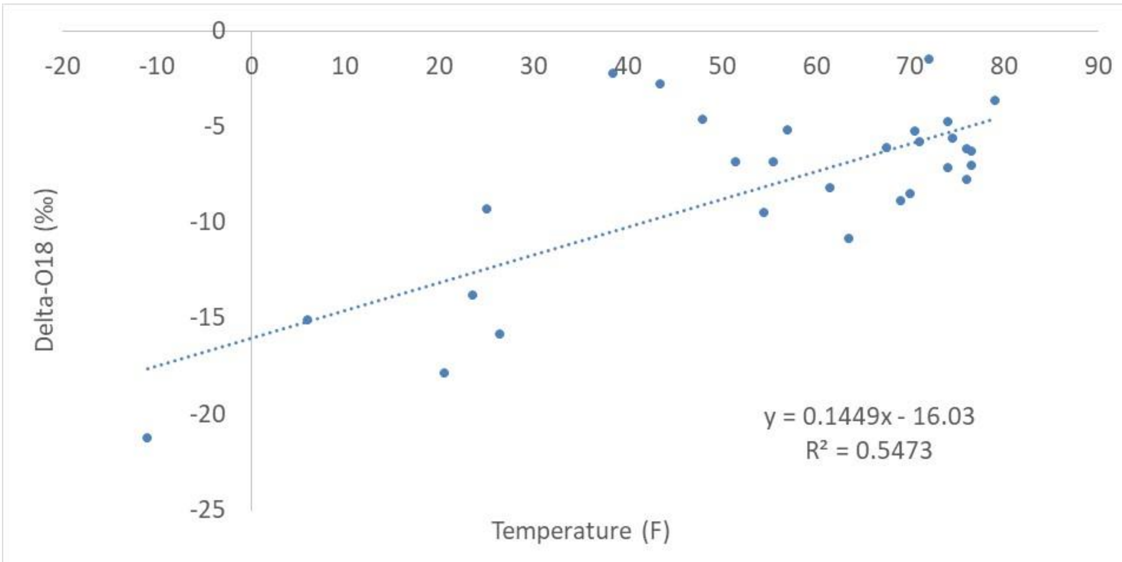


(c)

Figure 3- 3. LMWL and water sample isotope plots for each site. (a) is Waseca site; (b) is Tracy site; (c) is Beresford site

Linear relationship (Equation 3) between temperature and $\delta^{18}O$ was also established for all three sites (Figure 3-4). This relationship was used to determine the sine-wave function fit for the precipitation data for input function.



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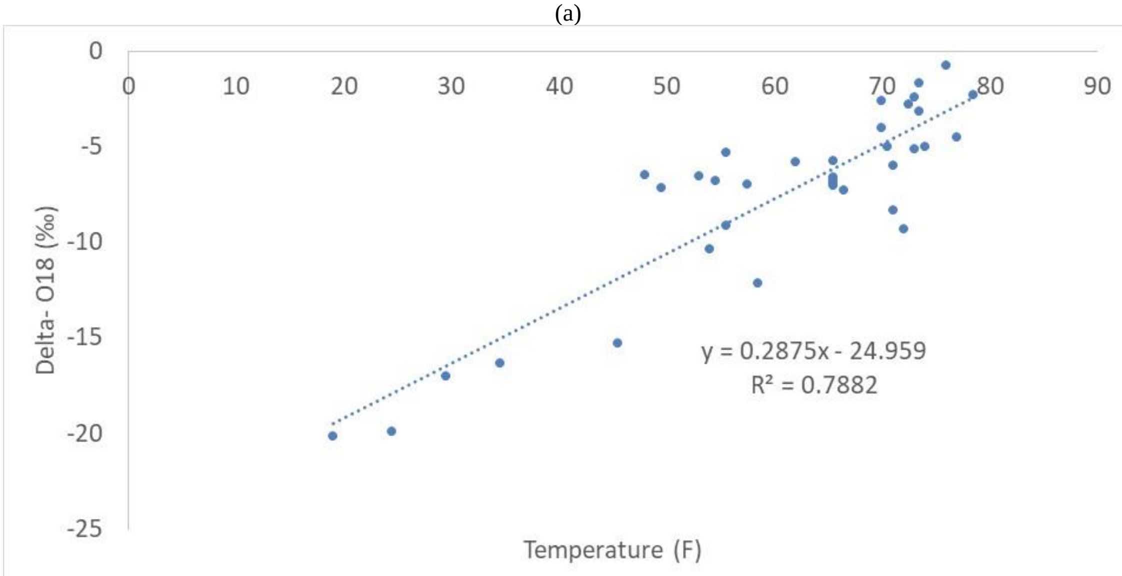

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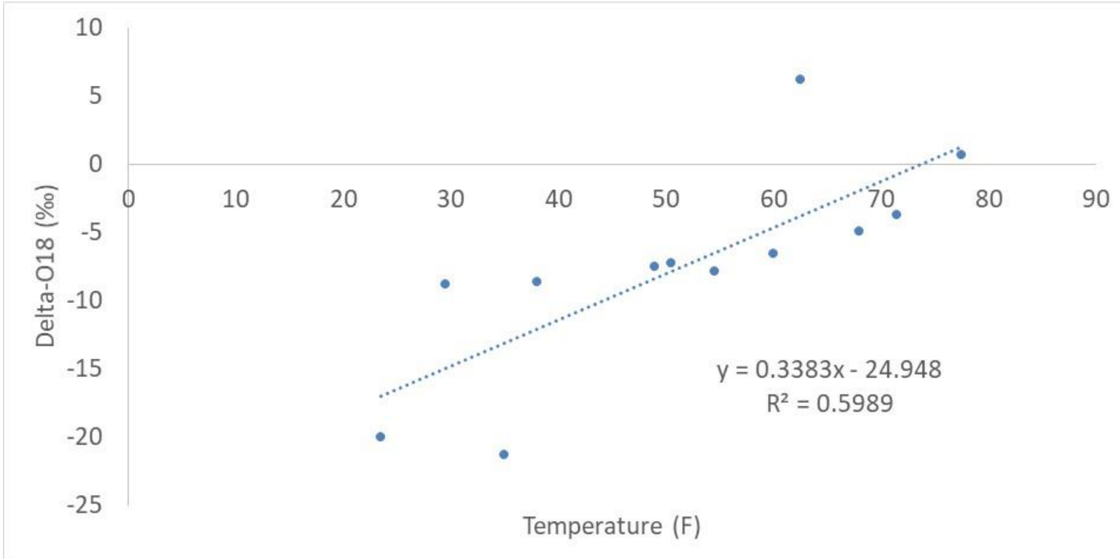

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Figure 3- 4. Linear relationship between temperature and δ^18 O at all three sites. (a) is Waseca; (b) is Tracy; (c) is Beresford

Input function was obtained by calculating weighted monthly $\delta^{18}O$ based on daily weather monitoring data using the above equations in the figures, and then adjusting with summer and winter infiltration rates (Equation 7). Equation 6 explains the assumption of the input water being mostly groundwater. Since tile flow contributed a large percent of the streamflow at these three sites (Chapter 2, Figure 2-5) and vadose zone water was not sampled and well-represented, recharge water (symbol as δ_{GW}) was assumed to be tile water average isotopic signature. The calculated infiltration coefficient for Waseca, Tracy, Beresford are, respectively, 0.39, 0.54, 0.16 using tile as recharge water. Since infiltration coefficient is the ratio of summer and winter infiltration amount, the number means winter infiltration exceeds summer infiltration by 1/α times. Taking Waseca groundwater recharge water as an example, infiltration coefficient of 0.25 means winter infiltration to groundwater exceeds summer infiltration by 4 times. This makes sense as winter snow melt infiltrates into the soil and in the summer, a larger portion of soil water is lost due to evapotranspiration.

The shape of the weighted monthly $\delta^{18}O$ curve suggests an absolute sine-wave function as below (Equation 9). The approximate function parameters for each site were calculated using the least-squares method. The parameters are shown in Table 3-3.

$$\delta^{18}O = A|\cos(\omega t - \varphi)| + S \quad (9)$$

Where:

The radial frequency constant, ω, in the sine-wave function is $2\pi/12$ radians d^{-1}.

Table 3- 3. Subsurface sampling depth at each site (from shallow to depth)

	A	φ	S
Waseca	4.5	3.8	-8.5
Tracy	7	3.35	-8.5
Beresford	10	4.56	-6

The MTT was solved using Excel Solver least-squares method. The results are presented in Table 3-4. The Exponential-Piston-Flow model parameter η is the ratio of total flow volume to volume of exponential flow. When η is approaching 1, the system is close to 100% exponential flow; when η is larger (greater than 6), the system is closer to piston flow.

Table 3- 4. Water mean transit time at each site

Location	EPM MTT (month)	EPM η	EPM RMSE	Sine wave (month)
		Waseca		
12” Tile	3.01	1.01	0.36	3.85
6” Tile	4.24	1.07	0.34	6.22
Well	4.76	1.08	0.35	16.36
River	3.76	1.06	0.29	2.74
		Tracy		
Tile	6.01	1.41	0.77	17.6
Well	15.75	1.81	0.28	21.81
Lysimeter	2.98	1.10	0.50	14.38

Piezometer	4.77	1.08	0.60	13.51
River	4.67	1.27	0.40	7.34
Wetland	4.47	1.04	0.28	4.66
		Beresford		
Tile	5.3	1.14	0.39	21.21
Shallow well	6.94	1.23	0.25	25.47
Deep well	9.78	1.37	0.23	41.93
Vermillion River	4.27	1.11	0.50	10.37

3.5. Discussion

There has been misunderstanding that water enters the tiles from the top by gravity. In Figure 3-3, the relative plot locations between groundwater wells and tiles further explained how water enters the tiles. At all three sites, there was a certain level of overlapping between well water isotopic signatures and tile water isotopic signatures, meaning that tile water has groundwater mixed in. For groundwater to enters the tiles, the water table needs to raise to allow that. The zone between tile and groundwater aquifer is saturated during tile flow and water from groundwater, vadose zone, and precipitation has a certain level of mixing, causing of isotopic signature overlapping between deep well and tile. Therefore, water enters the tile from the bottom due to water table raises, not from top.

The water MTT calculations agreed with the LMWL plot (Figure 3-3). Both Waseca and Beresford plots indicate high groundwater impact which was also shown by the MTT estimation that other water MTTs are closer to the well water MTT compared to Tracy site. However, the sine wave model predicted different MTT compared to the lumped parameter. The sine wave model highly depends on the accuracy of annual amplitude estimation. Due to the sampling limitations, the amplitudes could not be accurately estimated with the available data. Therefore, at locations where more data was available, the two MTTs were more comparable.

The MTT of tile water indicates the average time that precipitation infiltrates into the soil and raises the water table, then moves into the tile. This is the time given to microbial community for nutrient removal before the excess nutrient leaves subsurface zone with water. However, water movement from soil surface to the water table also picks up nutrients trapped in the soil, and, the zone is unsaturated and does not provide anerobic condition for nutrient removal. Therefore, practices that help prolong this time will be beneficial to nutrient removal.

3.6. Conclusion

Isotope is a tool of many benefits. It can be used for hydrograph separation and visually explains evaporation magnitude. It also helps characterize watershed water transport. Its nature of conservative tracer makes it less complicated than some other tracers such as bromide. Both HRT and MTT of water moving through subsurface are difficult to estimate due to the complexity of subsurface soil matrix and preferential flow path. Selecting system model and making recharge assumptions is critical in isotope tracer modeling when using lumped parameter analysis. Despite difficulties associated with the modeling processes, this analysis provides useful information to the overall water balance/water budget and helps better understand the water movement and mixing mechanism in subsurface zones. The information provided by this analysis can be used to guide water management and farming practices in agricultural lands. The MTT information can help gain better understanding on residence time in the soil profile for nutrient removal. The LMWL plots can visually explain groundwater input in wetlands and streamflow. From a water chemistry perspective, groundwater can bring higher levels of chemicals, such as calcium, into the surface water. From a hydrology perspective, this represents the baseflow in the stream and is important to know when developing nutrient removal strategies.

As seen in this model result, root zone water transport remains complicated. Future research can be done to characterize water from different soil horizons to relate soil evaporation to the transport behavior.

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